36421138043 34713200.510638 76802756.958333 36356276.5 2964733.9027778 16892293.888889 6184646.173913 68112604035 2274167826 165213714.2 5672164.9462366 112962828187 13360792.909091 160219576614 133536848.3125 44670581802 50292922.789474 103322463496 180928918.66667 12839156.362637

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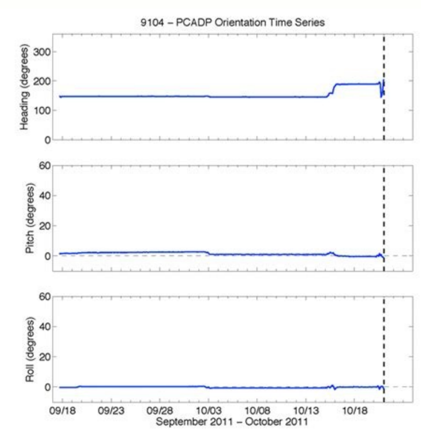

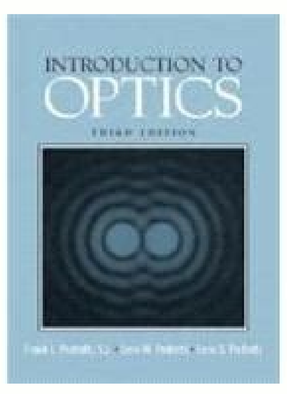

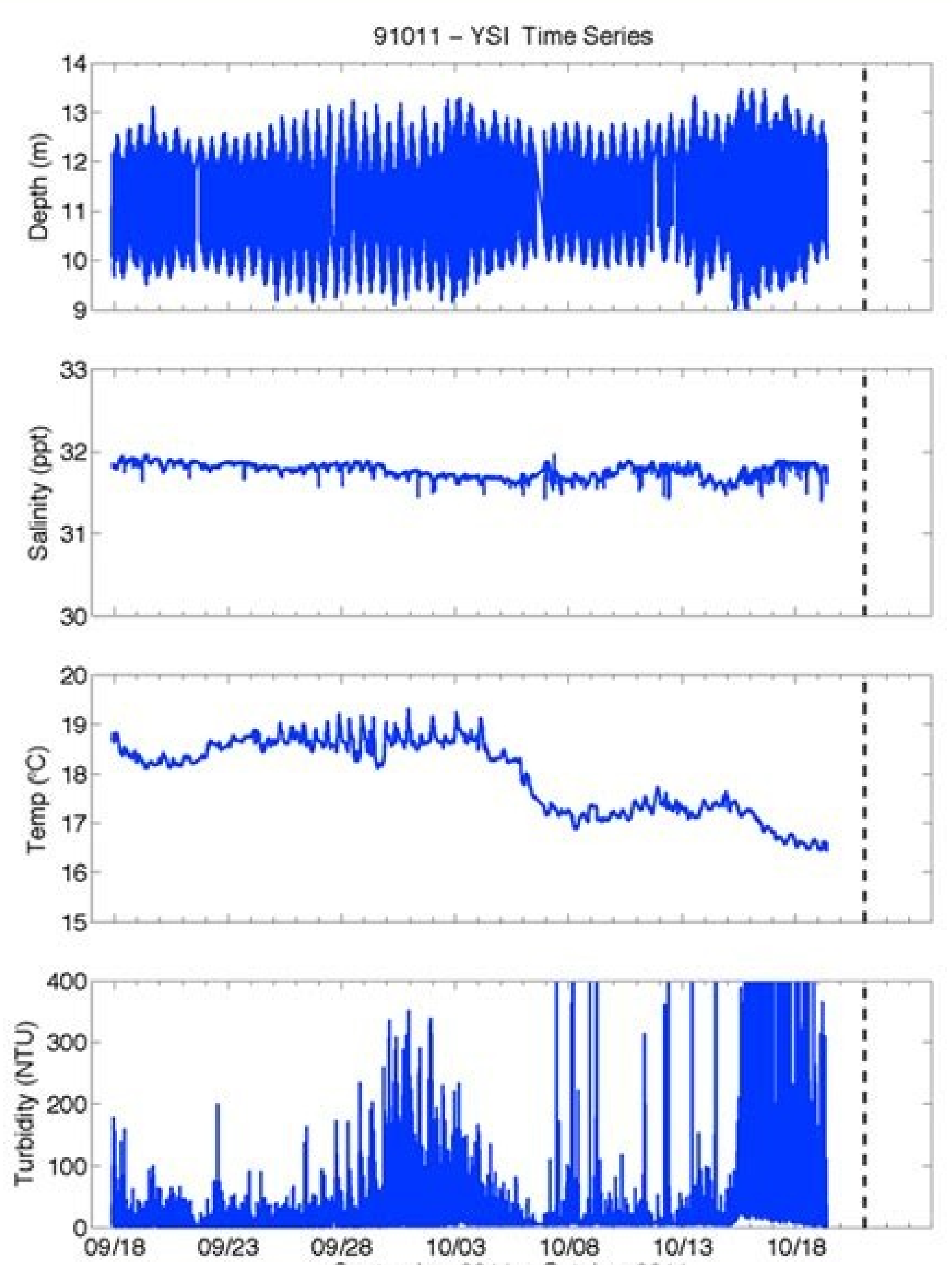

Why is fiber optics best for long distances. What is fiber optics used for. What is fiber optics made of.

Therefore, the ratio of the likelihood that a hydrogen atom will have energy E2 to the likelihood it will have energy E1 is a factor of 8 larger than the fraction given here. Mach-Zehnder Fiber Interferometers We will show here that a Mach-Zehnder fiber interferometer can be used to demultiplex (and multiplex) an optical signal containing a number of different wavelength channels. An object is placed (3/2)f from 27 A lens is moved along the optical axis between a fixed object and a fixed image screen. 7 The angular diameter of the sun viewed from the earth is approximately 0.5 degree. Here TEM stands for transverse electric and magnetic. (b) Cutaway view of a 35-mm camera, revealing the multiple element lens. Boston: Adam Hilger Ltd., 1986. Replacing p>2 by 1 - p>22 in Eq. (8) gives the normalized Jones vector, ' E0 = 1 d 22 - i 1 c t T/8 Ey A sin p/4 Ex A cos p/4 (c) the tip of the resultant vector traces out a circle of radius A. A Fourier analysis of the square function gives the Fourier series f1Y2 = 2 1 1 1 + acos kY - cos 3kY + cos 5kY + Á b p 2 3 5 (24) Here we find a constant 1k = 02 term of 12 corresponding to the DC component or central spot of the diffraction pattern; a term with fundamental (spatial) frequency, k1 = 2p>d; and terms with higher odd harmonics, 3k1 , 5k1 , Á . Karim, Mohammad A. Fizeau fringes result. The lens is 1 cm thick and has a refractive index of 1.50. The preceding discussion is but an introduction to the important role that polarization plays in light propagation through optical fibers.4 Here we simply conclude by noting that birefringent fibers can be used to make quarterand half-wave "plates" and phase compensators. 393 Optical Detectors and Displays Vertical scratches Unpolarized light Orientation of liquid crystal molecules Vertical polarization Polarizing sheet (Vertical transmission axis) Horizontal scratches Horizontal polarization Liquid crystal Glass plate Twisted nematic cell Glass plate Transmitted light Polarizing sheet (Horizontal transmission axis) (a) Vertical scratches Orientation of liquid crystal molecules Horizontal scratches Light polarization Unpolarized light Vertical polarization Vertical polarization Polarizing sheet (Vertical transmission axis) No transmitted light Liquid crystal Glass plate Twisted nematic cell Glass plate Polarizing sheet (Horizontal transmission axis) Applied voltage (b) Figure 9 Operation of a liquid-crystal display (LCD). That is, the wavefront is planar at the beam waist. The mirrors are attached to hanging mounts, which approximate free masses. 34 The primary mirror of a Cassegrain reflecting telescope has a focal length of 12 ft. However, the laser power is concentrated in a monochromatic directional beam of small cross-sectional area and so laser irradiances can be very high. For calcite, for example, n 7 n 7 , so that y 6 y7 : The Huygens' wavelet for the extraordinary ray is not spherical as in isotropic media but ellipsoidal as shown, with major axis proportional to y7 and minor axis proportional to y . What is the average illuminance of the parallel beam reflected from the mirror, assuming an overall reflectance of about 80%? The results of problem 5 will be helpful. In Figure 6, the intersection of several bright fringe surfaces with a plane that includes the two sources is shown, each surface corresponding D B D B S1 D B S2 Figure 5 Alternating bright and dark interference fringes are produced by light from two coherent sources. In 1926, the chemist Gilbert Lewis suggested the name "photon" for the "quantum of light" and it has been so identified ever since. (21) and (22) to form the last term in Eq. (24). (a) Right-angle prism. For A = 30°, the error is about 5%. Although their amplitudes vary with time, all pass through zero at the fixed nodal points. To record these phase relationships as well, it is necessary to convert phase information into amplitude information. The law of reflection ensures that pairs of triangles like SNP and S¿NP are equal, so all reflected rays appear to originate at the image point S¿, which lies along the normal line SN, and at such a depth that the image distance S¿N equals the object distance SN. This version of a grating spectrograph allows more compact construction than does the Paschen-Runge design. If the two object positions are S1 and S2 and if the transverse magnifications of the image are M1 and M2 , respectively, show that the focal length of the lens is given by f = a 1S2 - S12 30 Determine the ratio of focal lengths for two identical, thin, plano-convex lenses when one is silvered on its flat side and the other on its curved side. The forward beam shows the same polarization as the incident light. 42 Chapter 2 Geometrical Optics 11 NEWTONIAN EQUATION FOR THE THIN LENS When object and image distances are measured relative to the focal points F of a lens, as by the distances x and x¿ in Figure 26, an alternative form of the thin-lens equation results, called the Newtonian form. Moreover, D = af>a0 is the angular magnification. The equations yielded a prediction for the speed of an electromagnetic wave in the ether that turned out to be the measured speed of light, suggesting its electromagnetic character. Determine the coherence length for second harmonic generation in KDP when subjected to pulsed ruby laser light at l0 = 694 nm. The choice of label will depend on the manner in which the radiation is either produced or used. What is the rotation due to optical activity by a halfwave plate of quartz using the same light beam? Applying Rule 2 to Figure 15, we see that the general Eq. (12) becomes identical with Eq. (11), a special case derived in conjunction with Figure 15. The ability to control the temporal delivery of laser energy is important in a wide variety of applications, including materials processing, characterization of fast processes, and laser fusion technology. With the help of the Law of Malus, determine the value of N such that the final transmitted irradiance is IN = 0.9 I0 when the small angle wavefront tangent to the wavelets. (21) and (22) must be satisfied for efficient demultiplexing. Determine the focal length of the combination, distance from negative lens to film plane, and image size of a distant object subtending an angle of 2° at the camera. Assume photopic vision. Englewood Cliffs, NJ: Prentice-Hall, 1988. Generalizing, then for a multilayer of arbitrary number N of layers, c Ea E d = M1M2M3 Á MN c N d Ba BN An overall transfer matrix, MT , representing the entire multilayer stack is the product of the individual transfer matrices, in the order in which the light encounters them, MT = M1M2M3 Á MN (26) We return now to Eqs. Accordingly, since we require merely a relative phase of zero, we set wx = wy = 0. Chapter 3 Cox, A. Such a single-mode laser has a longer coherence length than a multimode laser. On the other hand, UV radiation has the beneficial effect of inducing vitamin D production in the skin. Projected surface A cos u Ap r Normal 13 Nature of Light intensity I(0) is observed. Alternatively, the refractive power of the eye itself can be altered through surgical procedures that reshape the cornea. (b) Side view before and after cuts. Of course, the straight line can be considered a special case of the ellipse, as can the circle. (b) Phasor components. 6 Plot a curve of total deviation angle versus entrance angle for a prism of apex angle 60° and refractive index 1.52. In this way we can fabricate optical elements that act as phase retarders. If Eq. (1) is multiplied by dt and integrated over one period T, the sine and cosine integrals vanish, and the result is a0 = 2 T Lt0 t0 + T f1t2 dt (2) If Eq. (1) is multiplied throughout instead by cos nvt dt, where n is any integer, and then integrated over a period, the only nonvanishing integral on the right side is the one including the coefficient an , and one finds an = 2 T Lt0 t0 + T f1t2 cos nvt dt (3) Similarly, multiplying Eq. (1) by sin nvt dt and integrating gives bn = 2 T Lt0 t0 + T f1t2 sin nvt dt (4) Thus, once f(t) is specified, each of the coefficients a0 , an , and bn can be calculated, and the analysis is complete. 13 A single slit of width 12 millimeter is illuminated by a collimated beam of light of wavelength 540 nm. We have also made use of Eq. (19) and identified the distance BQ with a quantity r¿. We choose, therefore, as a trial solution for the laser beam's electric field E1x, y, z, t2 the form ' E1x, y, z, t2 = U1x, y, z2ei1kz - vt + f2 (6) The term U(x, y, z) describes a departure from a "pure" plane wave and, when determined, provides the details that accurately specify the irradiance and phase variations of the wave. The degree of monochromaticity of a light source can be specified by giving the linewidth of the radiation. In GaAs doped with zinc, the zinc replaces gallium (three outer-shell electrons) in the lattice. Multifocal lenses, in which the power gradually increases from the top to the bottom of the lens, are now available. Proceeding thus we write, i1a1 - vt2 ER = Re1E01e + E02e i1a2 - vt2 2 = Re1e -ivt 1E01e ia1 E02 E0 a a2 E01 a1 + E02e 22 ia2 (a) Defining E0eia = E01eia1 + E02eia2 (8) permits the resultant wave to be expressed in the standard form, a ER = Re1E0ei1a - vt22 = E0 cos1a - vt2 a2 E01 The amplitude and phase of the resultant field can be found conveniently by treating the complex numbers in Eq. (8) as vectors, as indicated in the phasor diagrams of Figure 3. If the first, third, fifth, etc., of the 16 zones shown in Figure 7 are transmitting, then Eq. (14) becomes A 16 = a1 + a3 + a5 + a7 + a9 + a11 + a13 + a15 with 8 zones contributing. The decrease in photon number density allows the population inversion to once again grow and there follows a back-and-forth trading of energy between the atomic population and the electromagnetic field as the system settles into steady state. This is the steady-state operating condition for the laser. the angular spatial frequency is kY = 2p13>d2 = 6p> 94.2>mm. For N similar double layers in series, M = 1MH1ML121MH2ML22 Á 1MHNMLN2 = 1MHML2N = 1MHL2N (49) Substituting the double-layer matrix, Eq. (48), M = D N - gL gH 0 0 - gH gL T = D a -nL N b nH 0 0 -nH N a b nL T (50) The matrix elements of the transfer matrix representing N high-low double layers of l>4-thick coatings in series are thus m11 = a - nL N b , nH m22 = a - nH N b , nL m12 = m21 = 0 (51) Using these matrix elements in the expression for the reflection coefficient, Eq. (36), we arrive at r = n01 - nL>nH2N - ns1- nH>nL2N n01 - nL>nH2N + ns1- nH>nL2N ns (52) 488 Chapter 22 Theory of Multilayer Films When the numerator and denominator of Eq. (52) are next multiplied by the factor 1 - nL>nH2N>ns and the result is squared to give reflectance, we have Rmax = c 1n0>ns21nL>nH22N - 1 1n0>ns21nL>nH22N + 1 d 2 (53) Example 2 A high-reflectance stack like that of Figure 8 incorporates six double layers of SiO2 1n = 1.462 and ZnS 1n = 2.352 films on a glass 1n = 1.482 substrate. Suppose this woman mistakenly puts the right contact lens in her left eye and the left contact lens in her right eye. When the scratch is viewed through the glass from a position directly opposite, where does the scratch appear and what is its magnification? It can be shown that the second-order term makes no contribution to polarization in an isotropic optical material or one having a center of symmetry. The normalized forms of the Jones vectors now must include a prefactor of 1> 2A2 + B2 . (14) and (17) can be expressed in terms of the corresponding electric field amplitudes through the generic relation c E = yB = a bB n (19) Writing the index of refraction for incident and refracting media as n1 and n2 , respectively, Eqs. Entrance pupil is the stop; exit pupil is 12 cm in front of the lens, with an aperture of 6 cm; image is 10.5 cm behind the lens, inverted, and 1.5 cm long. When a level of higher energy has a greater population density than that of a level of lower energy, we say that a population inversion exists. What are its Brewster's angles for both external and internal reflections? 7 Determine the one-dimensional autocorrelation function £ 111t2 for the sinusoidal function y = A sin1vt + a2. What is the thickness of a zeroth-order QWP? Using the contact lens, what is the new near point of this eye? When the aperture is circular, the integration is over the entire area of the aperture since both vertical and horizontal dimensions of the aperture are comparable. 1 HUYGENS' PRINCIPLE The Dutch physicist Christian Huygens envisioned light as a series of pulses emitted from each point of a luminous body and propagated in relay fashion Surfa c norm e al Plane incid of ence In Incident medium ni ci ra den y t ui d cte fle y e R ra u Plane contains surface normal, incident, reflected, and refracted rays. A "single-mode" optical fiber actually supports two orthogonal linear polarizations. 19 Plot the refractive index profile for a GRIN fiber of radius 50 mm and with n1 = 1.5 and ¢ = 0.01. An ideal pinhole limits the extent of the tungsten source and improves the spatial coherence of the light. 1.25 cm farther from the objective 32. The acoustic wave (see Figure 11) consists of a series of compressions and rarefactions (longitudinal vibrations) in atomic density and so a periodic—although small—variation of the refractive index about its normal Train of compressions and rarefactions High Low Incident light beam High Low ks k Bragg angle u High k u D 2u Low High Low Path difference ls Low ls Low High Figure 11 Variations in the refractive index of a medium due to the passage of a harmonic acoustic wave (left) and the scattering of an incident optical beam by the induced "planes" (right). That is, narrower pulses are composed of harmonic waves with a wider range of frequencies. That is, show that IR + IT = II . The radius of curvature of the spherical side is also 4 cm. Compare the irradiance with that of an ideal polarizer when unpolarized light is passed through two such sheets having a relative angle between TAs of 0°, 30°, 45°, and 90°. This ray leaves point P in Figure 17a, passes through point C for the concave mirror, strikes the mirror, and reflects back along itself. 240 Chapter 9 Coherence Example 2 Let the source-to-slit distance be 20 cm, the slit separation 0.1 mm, and the wavelength 546 nm. (43), (45), (46), and (47) are employed in sequence. Note that the spectrums of the extraterrestrial sunlight and the sunlight reaching the earth both consist of a continuous blackbody background "interrupted" by dips. When green He-Ne laser light (543.5 nm) is used, the measured rotation is 1330 min. (a) *Me* = 104 W/m2, *Ie* (= 0) = 7.96 W/sr, *Le* = 3180 W/m2-sr (b) 1.56 × 10−4 W (c) 35.9 W/m2 15. Actually, the curve shown is the luminous efficiency of the eye for photopic vision, that is, when adapted for day vision. Thus, in contrast to the PRK procedure, in LASIK surgery the corneal epithelium is not removed. 2 BEAM SPREADING According to Eq. (14), the angular spread ¢u of the central maximum in the far field is independent of distance between aperture and screen. B = 0. In tungsten arc lamps, an arc discharge between two tungsten electrodes heats the electrodes to incandescence in an atmosphere of argon, providing a spectral distribution of radiation like that of tungsten lamps at 3100 K. They are called localized fringes because they are, so to speak, localized at infinity. This choice sets z0R = 0 and so q102 = iz0I . With regard to the first of these, it can be shown that the surface area Sn of the nth Fresnel zone is given by Sn = pr0œ r20 l l 2 c + 12n 12a b d r0 + r0œ r0 2r0 (15) Figure 4 (a) Fresnel circular half-period zones on a spherical wavefront emerging from an aperture. A schematic of this device is shown in Figure 8. 21 Trace two rays through the hemispherical lens of Figure 15. That is, the steady-state output of the laser includes electric fields with frequencies corresponding to many different cavity resonances. The direction of the dipole moment is from the negative toward the positive charge. 32, 33. Q-switching can be accomplished by mechanical means, such as rotating a cavity mirror into and out of alignment or passing a miniature fan blade through the cavity. 17 Find the transmittance, T = IT>II , and the reflectance, R = IR>II , of a Fabry-Perot cavity with mirrors of (internal) reflection coefficients r1 and r2 Z r1 . These effects can be shown to lead to a Lorentzian lineshape function, g1n2 = ¢nH 2p[1n - n022 + 1¢nH>222] (49) This function peaks at n = n0 and has a full-width at half-maximum of ¢nH . Relations Between the Einstein A and B Coefficients Einstein was able to establish a relation between the Einstein A and B coefficients by showing that thermal equilibrium will exist between a radiation field and an assembly of atoms if the following relations hold: A21 = 8phn3>c3 B21 (12) B12 = B21 (13) and These relations are necessary for thermal equilibrium between an assembly of atoms and a radiation field to exist but hold generally as well, since the Einstein A and B coefficients are characteristics of the atomic levels. High-power CO2 lasers are sometimes pumped by electron beams or gas dynamic processes. For example, we shall give the free spectral range of a variable-length Fabry-Perot interferometer the symbol dfsr and that of a variableinput-frequency Fabry-Perot interferometer the symbol nfsr . Thus the condition for removing lateral chromatic aberration is the coincidence of the principal planes for the two corrected wavelengths. This change in sign restores the proper phase relation between the dipoles and the second harmonic field and so ensures continued amplification of the second harmonic field. Thompson, Physics of Semiconductor Laser Devices (New York: Wiley-Interscience, 1980). 562 Chapter 26 Laser Operation rearrangement, we find IL = IS a g0L - ln11>S2 b 1 - S The irradiance of the laser beam exiting the ring cavity is, then, Iout = T3IL = T3IS a g0L - ln11>S2 b 1 - S (43) Let us examine the features of this expression. T shape, such as that shown in Figure 1. In general, plane monochromatic waves are elliptically polarized, in the sense that, over time, the tip of the electric field vector in a given plane perpendicular to the direction of energy propagation traces out an ellipse. Hecht, Eugene, and Alfred Zajac. 2 PARTICLES AND PHOTONS Photons and electrons that behaved both as particles and as waves seemed at first an impossible contradiction, since particles and waves are very different entities indeed. If I0 represents the maximum transmitted irradiance, then Malus' law states that the irradiance for any relative angle u between the TAs is given by I = I0 cos2 u (1) Malus' law is easily understood in conjunction with Figure 2. 9 In what kinds of media are both longitudinal Pockels and Kerr effects present? Figure 9 shows schematically the Faraday rotator, a crystal or liquid cell whose axis of symmetry is aligned with a magnetic field. A similar argument for the zones below the axis would lead to a twin spiral, represented in the third quadrant and connecting at the origin O. 17 Express the plane waves of Eqs. (6) and (7), I12 = e0cE01 # E028cos d9 B B (9) 166 Chapter 7 Interference of Light The irradiance terms I1 and I2 of Eq. (5) can be shown to yield I1 = e0c8E1 # E19 = e0cE2018cos21a - vt29 = 1 e cE2 2 0 01 (10) I2 = e0c8E2 # E29 = e0cE2028cos21b - vt29 = 1 e cE2 2 0 02 (11) B B and B B In Eqs. The drawings in Figure 6, 431 Optics of the Eye Hyperopic eye (corrected) Hyperopic eye (unaided) Blurred vision Distant object Hyperopic F.P. Lens (positive power) Distant object No accommodation (a) H.F.P. Distinct vision Distant object Distinct vision No accommodation (d) Nearby object at N.N.P. Partial accommodation (b) Nearby object at H.N.P. H.N.P. N.N.P. Distinct vision H.N.P. N.N.P. Distinct vision Full accommodation (e) Full accommodation (c) Figure 6 Hyperopic vision with correction. Whereas most excited levels in an atom might decay in times of the order of 10-8 s, level E2 is metastable, with a typical lifetime of the order of 10-3 s, hundreds of thousands of times longer than other levels. 92 Chapter 3 Optical Instrumentation 6 c. The solid lines represent the maximum displacement of the wave. In the photovoltaic (forward-biased) mode, the open-circuit voltage has a more complicated logarithmic dependence on the incident irradiance. Conversely, when the grid intercepts waves polarized in a direction perpendicular to the wires, there is efficient transmission of the waves. Matched filtering techniques using incoherent light have also been devised to reduce the signalto-noise background that is typical in coherent light systems. Chapter 25 Feynman, Richard P., Robert B. (19) and (22) for R(z) and w(z), we can integrate the resulting equation to obtain p1z2 = l2z2 + 1pw2022 lz i ln c d - 1m + n + 12arctanc d 2 2 2 1pw02 pw20 (64) Here we have also used Eq. (21) to eliminate z0 in favor of w0 and l. (a) 122 nm, 103 nm, 97.3 nm; ultraviolet (b) 656 nm, 486 nm, 434 nm; visible. Radiating area AS R Nature of Light 15 b. The shape of the comatic image is such that its maximum extension is three times the radius of the comatic circle formed by rays from the outer zone of the lens. If the pump is still operating, this atom is ready to repeat the cycle, thereby ensuring a steady population inversion and a constant laser beam output. Two rays reflected from each are shown labeled as (1) from M1 and (2) from M2 . 5 A 596-Å-thick layer of ZnS 1n = 2.352 is deposited on glass 1n = 1.522. (8) and (9) are true whether or not the atom is in thermal equilibrium. Second, each of the vectors in Table 1 can be multiplied by a factor of the form eiw, which has the effect of promoting the ' E0xeiWx TABLE 1 SUMMARY OF JONES VECTORS E0 = c d E0yeiWy I. The pyroelectric metal behaves like a capacitor whose charge is a function of the temperature. The emulsion, however, is incapable of responding linearly to all irradiances, varying from zero to maximum, so that the developed plate will show a distorted cos21ar22 transmittance and higher-order diffractions will not be suppressed. Why? The normal PD drawn for this ray is used to define angles of incidence and reflection for the beam. Better color resolution can be obtained by using three separate CCDs in the camera. Notice also that some amplitudes may be negative, that is, some harmonic waves must be subtracted from the sum to accomplish the convergence. The technique is well adapted to iterative loops handled by computer programs. Thus, it can be seen in Figure 11a that for aperture position (1), the average distance PM for the shaded pencil is greater than the average distance PN for the lower pencil. u = l 200 * 10-9 m = = 2.55 * 10-5 rad pw0 p12.5 * 10-3 m2 This represents, roughly, a 30-fold decrease in beam spread over the He-Ne laser described in part (a). perpendicular to the planes x + y + z = constant ' ' ' ' 12 Show that if z is a complex number, (a) Re 1z 2 = 1z + z *2>2; ' ' ' (b) (c) Im1z 2 = 1z - z *2>2i; cos u = 1eiu + e-iu2>2; (d) sin u = 1eiu - e-iu2>2i. An extended source is used in conjunction with a beam splitter set at an angle of 45° to the incident light. Let the reference beam be represented by the complex electric field ER = rei1vt + w2 (1) at the plane of the film. The difference in wavelength of the emitted waves and that of those detected after reflection is directly related to the velocity of the particulates relative to the source of the radar. Nonlinear Optics and the Modulation of Light designed for efficient second harmonic generation using light with a phase mismatch ¢k. After a rather thorough study of the fundamental mode of the laser beam, we shall examine the higher-order transverse modes and their transverse irradiance distributions. Show that the magnification of a doublelens eyepiece, designed to satisfy the condition for the elimination of chromatic aberration, is, for an image at infinity, 27 A pair of binoculars is marked "7 * 35." The focal length of the objective is 14 cm, and the diameter of the field lens of the eyepiece is 1.8 cm. Fringes of equal inclination are focused by a lens. In the optical arena, the beat phenomenon can be used to measure the difference between the emitted radar wave and the Doppler-shifted return signal in a Doppler weather radar system or as part of a feedback loop designed to ensure that two sources have the same frequency. Suppose that nf 7 n0 and nf 7 ns . The disturbance c may refer to transverse displacements of a string or longitudinal Irradiance variation in transverse plane x, y x0, y0 x0, y0 1 Irradiance profile line e2 w(z) u l pw0 w0 z Waist Wavefront Figure 9 Gaussian beam propagating in the z-direction. The origin y = 0 corresponds to z = 0 and therefore to the y-axis through the aperture of Figure 11a. near, near, far maxima: 409, 136, 81.8 cm; minima: 204.5, 102, 68 cm (a) 1.88 and 3.26 mm (b) 2.66 and 3.76 mm (a) 0.0346 cm (b) 833 (c) 20 cm, 6.67 cm, 4 cm (a) 0.02 cm (b) 2500 (a) 4 × (b) very nearly zero (c) 5; 6 (a) (b) (c) (d) 3. Unpolarized Light Often the individual atoms in a source, at a given instant, emit light with differing random polarizations. 7 In forming an image of an axial point object, a + 4.0-diopter lens with a diameter of 6.0 cm gives a longitudinal spherical aberration of +1.0 cm. Each beam is again totally reflected by mirrors M1 and M2, and the beams are made coincident again by the semitransparent mirror M3. Duffieux, P. What photocurrent is where n is the mean number of photons in the field. As we have seen, temporal coherence is a measure of the average length of the constituent harmonic waves, which depends on the radiation properties of the source. The figure shows a field B established by current windings and indicates a rotation of the polarization in the same sense as the current producing the field. The light-gathering capability of the objective lens is thus increased by increasing the refractive index in object space. Michelson himself pioneered much of this work. The critical angle for refraction into air is given as usual by B sin uc = 1>n and so depends on the orientation of the E-vibration relative to B B the OA. Linear and Elliptical Polarizations We conclude this section with but a brief discussion of the basic nature of the polarization of harmonic electromagnetic fields. The difference in the frequencies of adjacent standing wave modes of the cavity d. Let the field incident on a Fabry-Perot cavity be removed at time t0 . 68 Chapter 3 Optical Instrumentation B 30 45 A 30 E 45 90 C D L Figure 17 Pellin-Broca prism of constant deviation. Thus the optical path length ¢ 1 479 Theory of Multilayer Films associated with one traversal is ¢ 1 = ¢>2 = n1t cos1ut12, and phase difference d that develops due to one traversal of the film is d = k0 ¢ 1 = a 2p b n t cos ut1 l0 1 (15) Thus, Ei2 = Et1e -id (16) Ei1 = Er2e -id (17) In the same way, Using Eqs. To prepare for a comparison with Gaussian beams that are confined near the z-axis, we will develop an approximation to Eq. (29) that is valid near the z-axis and away from the beam waist, that is, where r V ƒ z ƒ . At the center of the macula, located somewhat above the optic nerve, is the fovea centralis, the region of greatest visual acuity. The lateral field of view processed by this optical system is at most a circle of radius OV. The lens has a refractive index of 1.52. Example 4 Calculate the penetration depth of an evanescent wave undergoing TIR at a glass- 1n = 1.502 to-air interface, such that the amplitude is attenuated to 1/e of its original value. Chapter 6 O'Shea, D. The matter of temporal coherence requires a comparison between the path difference ¢ = SAP1 - SBP1 and the coherence length of the radiation. Ronchi, Vasco. 5 Show that Eq. (58) for the skin depth at low frequency is an adequate approximation when v g and v s>e0 . 10 m/s in +x-direction 5. In contrast, as we shall see in the next section, many different cavity modes can lase in a system that uses an inhomogeneously broadened gain medium. N., and D. On the other hand, the velocity of the envelope, called the group velocity, is yg = vg kg = v1 - v2 dv k1 - k2 dk (37) assuming again that the differences between frequencies and propagation constants are small. Er u k E Normal B x 495 Fresnel Equations and B B # B B = - ByN ei1k r - vt2 B B # (16) B Br = BryN ei1k r - vt2 B B # (16) B Bt = - Bt yN ei1kt r - vt2 Requiring continuity of the components of the electric and magnetic fields that are parallel to the boundary gives, in this case, - B + Br = - Bt (17) E cos u + Er cos u = Et cos ut (18) Reflection and Transmission Coefficients The magnetic field amplitudes of Eqs. The gain coefficient becomes larger as k10 is increased relative to the decay rates associated with level 2. Using the irradiance of Michelson fringes as a function of phase, calculate (a) the fringe separation; (b) the fringe width at half-maximum; (c) their ratio, the finesse. Flash lamps and arc lamps are often used as optical pumps for laser systems (like Neodymium:YAG) using solid-state gain media. We know that, near the aperture, more rigorous methods must be used that take into account the vector properties of the electromagnetic field, including polarization effects. R. Since real object distances are positive, what does your result imply for the cases n2 7 n1 and n2 6 n1? One of the rays (shown) passes through the wedge in a symmetrical fashion, making equal entrance and exit angles with the two sides and satisfying the condition for minimum deviation. Maiman at the Hughes Research Laboratories in 1960, was a pulsed ruby laser, which operated at the visible red wavelength of 694.3 nm. Suppose a 2000-W laser beam is concentrated by a lens into a cross-sectional area of about 1 * 10-6 cm2. Recently, several different technologies have been developed that allow for displays that are less bulky and/or use less power than CRT displays. System Evaluation Using the Transfer Function Characterization of the imaging capacity of an optical system by simply citing its resolving power does not give an adequate assessment of the system's performance. The interference of light waves provides the requisite means. Notice that beam 3 traverses the beam splitter three times, whereas beam 2 traverses it only once. 5 Show that the rest-mass energy of an electron is 0.511 MeV. This telescope is large enough so that the observer can be mounted on a specially built platform situated just behind the primary focus (Figure 35). Check your calculations against Figure 2. s y p f1 w f2 q Matrix Methods in Paraxial Optics PP1 n0 409 nf a F1 yf y0 H1 a0 r p f1 Output plane Input plane (a) PP2 y0 ⩾af yf H2 s ⩾af F2 q f2 Output plane Input plane (b) ⩾w y N1 ⩾y0 a a a yf N2 Figure 12 (a) Construction used to relate distances p, r, and f1 to matrix elements. If yP̂ 7 yĉ , the P̂ mode reaches some point B along its path before the ĉ mode. PROBLEMS B 1 Show that when the incident E-field is parallel to the plane of incidence, g1 has the form given in Eq. (37). The top part of the spiral (z 7 0 and y 7 0) represents contributions from strips of the aperture above the y-axis, and the twin spiral below (z 6 0 and y 6 0) represents similar contributions from below the y-axis. In addition to the key optical components encountered by light traveling along the axis of vision, the eye contains other components that should be mentioned. Suppose next that the linear polarizer has a TA inclined at 45° to the x-axis. However, since most of the power carried by the beam is concentrated near the z-axis, referring to the function R(z) as the radius of curvature of the beam is appropriate. The signs for so and si follow the usual sign convention. Snell's law requires, for the ray incident at the vertex V and in the small-angle approximation, n1u1 = n2u2 or, using tangents for angles, ho hi n1 a b = n2 a b s s¿ The lateral magnification is, then, m = hi n1s¿ = n2s ho (22) where the negative sign is attached to give a negative value corresponding to an inverted image. For a dielectric medium, the increase of dipole moments at resonance results in a large maximum polarization. If it is desired to have a fringe spacing of 1 mm at the screen, what is the proper screen distance? Is it magnified? The derivation of the Doppler effect for light requires the theory of special relativity and so is not carried out here. ' Using Eqs. (Courtesy Mitsubishi Rayon America, Inc.) 254 Chapter 10 Fiber Optics n2 Figure 9 Symbolic representation of modal distortion. 12 An important application of the QWP is its use in an "isolator." For example, to prevent feedback from interferometers into lasers by front-surface, back reflections, the beam is first allowed to pass through a combination of linear polarizer and QWP, with OA of the QWP at 45° to the TA of the polarizer. The image length AB can be found from a simple, geometrical argument that is apparent in Figure 32a, a view of the central horizontal section in Figure 31 as seen from above. Now, according to the grating equation, ml = d sin u = d Ym f (19) where d is the spatial period of the ruling. Nonlinear Optics and the Modulation of Light E1(z, t) E1(z, t) E0ei(vt ⩾ kz) 531 E0 i(vt ⩾ kr) e r M M E2(z, t) E0ei(vt ⩽ kz) (a) Plane wave E0 i(vt ⩽ kr) e r (b) Spherical wave E2(z, t) E1(r, t) Re[≠(r)ei(vt ⩾ kz)] M E2(r, t) Re[≠*(r)ei(vt ⩽ kz)] (c) "Nearly plane" wave words, the spatial part of the wave equation. This is the principal result of our calculation for axial object points. The relevant angles describing the progress of the ray through the prism are defined in Figure 9. Finally, in step 4, the neon atom in energy state 2p4 decays by spontaneous emission to the 1s ground level. Two coherent, monochromatic beams are made to interfere, producing standing waves in the region between the collimating lens C and a plane mirror M. Note that for all three curves, the irradiance input to the cell is I0 = 1 W>cm2. To appreciate the physics that underlies this phenomenon, consider Figure 4, which shows a narrow beam of light incident at an arbitrary angle on a smooth, flat, dielectric surface. The time-averaged irradiance for the k component at the detector is then Ik r 81E1 + E2229 which gives, Ik = 2I011 - cos kx2 (39) where I0 represents the time-averaged irradiance of one beam. Provide ray diagrams for each case. The condition 0P>0l = 0 applied to Eq. (36) now gives L = PPB PPR (48) which is the same result as for a double-lens eyepiece. For distant objects, the film must be situated in the focal plane of the lens. Taking into account the associated sign convention, the grating equation becomes ml = a[sin ui + sin12ub - ui2] (15) We consider two special cases of Eq. (15). 5 REFRACTION THROUGH PLANE SURFACES Consider light ray (1) in Figure 9a, incident at angle u1 at a plane interface separating two transparent media characterized, in order, by refractive indices n1 and n2 . Thus, for example, in the text and correlated Figures 1a, b, and c, we define carefully the meaning of aperture stops (AS), entrance pupils 1EnP2, and exit pupils 1ExP2 and illustrate their effects in several simple optical systems. In the following example we estimate the field strengths and irradiances required to make the nonlinear contributions to the polarization sizeable compared to the linear contribution. Thermal detectors using a blackened strip as a receptor may be nonselective; however, entrance windows to such devices may well make them selective. Problem 32 37 A plano-cylindrical lens in air has a curvature of 15 cm and an axial length of 2.5 cm. Show further, using the Fresnel Eqs. 11 Determine the theoretical content of the constants A, B, and C used to express the Cauchy dispersion equation. Radiation is absorbed at the junctions T1 in thermal contact with a black absorber and thermally insulated from the junctions T2 . Such results are surprising because they are not apparent in ordinary experience; yet they necessarily follow once Figure 5 is understood. Determine the thickness of the oil film and the orders of the interference. The light wave traverses the crystal with a speed that is around five orders of magnitude greater than the speed of the acoustic wave. Another Model of Imaging: Convolution In the preceding sections, we have presented imaging as (1) a result of diffraction or Fourier analysis, producing a spectrum of spatial frequencies; and (2) their subsequent recombination, or Fourier synthesis, to form the image. The inverse transform of the transform of a function f(x) returns the function f(x). In addition, c has the same value on all wavefronts separated by a wavelength l = 1 m. Since y = c>n, different refractive indices, nĉ and nP̂ , may be defined for circularly polarized light. The thin-lens equation can be used to determine the correct power for the spectacle lens, 1 1 1 + = s s¿ f or 1 1 1 + = 38 -148 f Optics of the Eye 1 1 Calculation gives f = 51 cm. New York: Academic Press, 1969. For other wavelengths the transfer matrix must be used in its general form, containing the wavelength-dependent phase differences. It follows that the radiance of the beam is also the radiance of the source, at the initial point of the beam, or L1 = L2 = L0 . 10 20 30 40 50 60 70 80 90 Angle of incidence u PROBLEMS 1 Show that the vanishing of the coefficient in the TM mode, Eq. (28), occurs at Brewster's angle, up = tan-11n2. PROBLEMS 1 Initially unpolarized light passes in turn through three linear polarizers with transmission axes at 0°, 30°, and 60°, respectively, relative to the horizontal. 4 A readable, comprehensive discussion of the helium-neon laser, with energy level diagrams and transition probabilities, is given in C. Christiaan Huygens, a Dutch scientist contemporary with Newton, championed a view (in his Treatise on Light) that considered light as a wave, spreading out from a light source in all directions and propagating through an all-pervasive elastic medium called the ether. The mean value of the visible spectrum may be taken at 550 nm. Assume a wavelength of 550 nm. As Example 1 illustrates, the energy of a photon is much less than the total energy stored in a typical macroscopic electromagnetic field and so the graininess of the electromagnetic field often goes unnoticed. Recall that the lowest possible temperature (so-called absolute zero) has the value 0 on the Kelvin temperature scale and that the temperature in Kelvins is related to the temperature in Celsius degrees via the relation TKelvins = TCelsius + 273. Determine the location and size of the entrance and exit windows. The resultant wave in the medium, by the principle of superposition, is ER = E1 + E2 = E0(sin(1t + kx2 + sin1t - kx - wR2)) (21) It is expected in this case to define b = + vt + kx and b = vt - kx - wR and employ the trigonometric identity sin b + sin b - k2 sin 121b + - b 2 cos 121b + - b 2 Applied to Eq. (21), this leads to the result ER = 2E0 cos a Kx + Mirror E1 ≤ E0 Node Node w b b sin a vt - R b 2 2 Node t T 3T 5T , , ... Figure 12 Double refraction. 154 Chapter 6 Properties of Lasers because, since the wave has a single frequency, knowledge of the phase at a given point (say, P1) at time t1 allows one to predict with complete confidence the phase of the field at point P1 at some later time t2 . 46 Chapter 2 s Geometrical Optics s C I O L B (a) I O s (b) Figure 32 (a) Light rays in a top view of the horizontal (nonfocusing) section of the lens in Figure 31. Or, as in Figure 17c, it strikes a convex mirror and reflects as if it came from the focal point F behind the mirror. Referring to Figure 3, the complex number z is represented in terms of its real and imaginary parts along the "y" coordinates. Whereas, as noted earlier, spontaneous emission is typically unimportant in visual-stage laser operation, it is essential in initiating the growth of the laser field. An advantage of the Mach-Zehnder over the Michelson interferometer is that, by appropriate small rotations of the mirrors, the fringes may be made to appear at the object being tested, so that both can be viewed or photographed together. At room temperature nearly all the atoms in a medium will be in the atomic ground state. Light of mean wavelength 550 nm from a distant star enters the scope as a nearly collimated beam. The projected area of the surface 1A cos u2 is shown by the dashed line. (6) and (10) for boundary (a), the result is Eia = Eb cos 4 + Eb a sin 4 b 1 Rb + Eb1 sin u2 + Bb cos d (22) (23) where we have used the Euler identities 2 cos d K eid + e -id and 2i sin d K eid - e -id Equations (22) and (23) relate the net fields at one boundary with those at the other. Shown in Figure 4 are two pencils of rays whose limits are determined by an aperture EnP serving as the entrance pupil. We summarize the basic equations for the thick lens without proof. The way in which energy is distributed in the radiation determines the color of the light and, consequently, the color of surfaces seen under the light. Note that both circular and linear polarizations represent limiting cases of elliptical polarizations. According to Eq. (34), z1 = z2 - d = - 6. The Soviet ophthalmologist, Svyatoslav N. Evanclinetal, variations are predicted to be a form of transverse quadrupole radiation so that a wave propagating in a direction that is perpendicular to the plane of the interferometer will induce changes in length of opposite sign in the two arms of the interferometer. 9 Using the equation for spherical aberration of a thin lens, see problem 8, find the longitudinal spherical ray aberration of a lens as a function of ray height h. The first five zeroes of the Bessel function occur at q = 0, q = 3.832, q = 7.016, q = 10.173, and q = 13.324. This is the case also for wavelets that have no large-scale crystalline structure, such as glass or fluids. 398 Chapter 18 Matrix Methods in Paraxial Optics principal points relative to the vertices V1 and V2 , while f1 and f2 determine focal point positions relative to the principal points H1 and H2 , respectively. New York: John Wiley and Sons, 1998. xs-variation of electric field Hermite polynomial Hm(xs)ex Hm(xs) xs-variation of irradiance Burn pattern for (xs, ys) plane [Hm(xs)exx /2 [2 2/2 2 H(xs) n0 H0(xs) 1 xs xs xs xs xs TEM00 H(xs) Figure 15 Laser-beam electric field and irradiance variations in the xs-direction for two values of the Hermite integer m. Measurement of the waves by their effect on the eye or some other light detector depends on the energy of the light beam. Field flattening by this condition cannot be accomplished for a single lens, but artificial field flattening may be accomplished by use of an aperture stop positioned as in Figure 9d. If the image of the 1n - 12 steps is not actually formed, it serves as a virtual object for the nth step. Thus, 1IT2max - 1IT2min 1 - 1>11 + F2 = F 1IT2min 1>11 + F2 (28) Note that this measure of fringe contrast, the coefficient of finesse, differs from the related quantity called the visibility. Pyroelectric Detectors The pyroelectric effect can be exploited in order to detect radiation. For each curve, we see that T = Tmax = 1 at d = m12p2, and T = Tmin = 1>11 + F2 at d = 1m + 1>22p. Only one process, stimulated absorption, drives the atom from level 1 to level 2. This is useful if one wishes to associate wR with the phase shift caused by reflection. By the scattering of light, we mean the removal of energy from an incident wave by a scattering medium and the reemission of some portion of that energy in many directions. The contribution dEp at an arbitrary point P due to the light amplitude from an elemental area dA surrounding point O in the aperture is given by dEP = a EA da /1vt - k2 be r (9) where r is the distance from point O to point P. Doping involves adding small amounts of an impurity to the semiconductor to provide either an excess (n-type) or deficiency (p-type) of conduction electrons. Find the group velocity for plane waves in a dispersive medium, for which vp = A + Bl, where A and B are constants. The curve represents the product of the interference and diffraction factors. Because of the absence of scattering, the illuminated side of the object can be seen very clearly. The brightness of the image cannot be greater than the brightness of the object; in fact, it is less bright due to inevitable light losses due to reflections from lens surfaces, a 3 THE OBLIQUITY FACTOR a0 2 P a a0 O a Figure 3 factor. If the stars are being detected by their long-wavelength infrared emissions—the lenses being replaced by dish antennas—the resolution may, by Eq. (22), be much less. TABLE 3 REFRACTIVE INDICES FOR QUARTZ l (nm) n7 n ne n° 396.8 162.0 1.56771 1.54811 1.55815 1.53917 1.55810 1.53914 1.55812 Production of Polarized Light 367 Solution From Table 3, at l = 396.8 nm, n° = n° = 1.55821 - 1.55810 = 0.00011 Using Eq. (10), b = p(10.92 396.8 * 10-9 10.00011 2 = 0.8709 rad = 49.9° in good agreement with Table 4 for the neighboring wavelength of 404.6 nm. 272 Chapter 11 Fraunhofer Diffraction l b 3.47 p b b 2.46 p y tan b b 1.43 p b 2p p 3p Figure 3 Intersections of the curves y = b and y = tan b determine the angles b at which the sinc function is a maximum. The distinction rests on the fact that the human eye, as a detector, does not have a "flat" spectral response; that is, it does not respond with equal sensitivity at all wavelengths. 536 Chapter 23 Theory of Multilayer Films 2 1 Characteristics of Laser Beams One can evaluate q1 as follows. Show that polarizing angles for internal and external reflection between the same two media must be complementary. The pinhole itself must be accurately formed in an ideal disk and can be ignored to be always parallel to the cylinder axis. This remedy for spherical aberration is, of course, accompanied by a reduction in image brightness. (Reproduced by permission from "Atlas of Optical Phenomena", 1962, Michael Cagnet, Maurice Francon and Jean Claude Thrierr. Plate 12. In its simplest description, diffraction is any deviation from geometrical optics that results from the obstruction of a wavefront of light. This spot, devoid of any receptors, is appropriately called the blind spot. It requires the multiplication of one function at each point by the whole of another function and then the summation of the results. (Negative values of adb indicate amplification, rather than attenuation!) Dramatic advances have been made in reducing the absorption of fused silica so that today, fibers rated at 0.2 dB/km (operating at 1.55 mm) are readily available. 10 Joseph C. At incidence, the linearly polarized light is immediately resolved into ° and P circular modes, which, at z = 0 and t = 0, begin together with u° = uP = 0. Determine q2 , the complex radius of curvature at the external beam waist by using the ABCD propagation law. Rather, the various harmonic waves that combine to produce the wave train must be numerous and so selected that they produce strong constructive interference only within a certain range and strong destructive interference beyond this range. Taken together, the various orders of the atomic groups and not all cavity modes initially above threshold will lase. High-resolution plates are used to record this information faithfully. 2 3 HOLOGRAM OF AN EXTENDED OBJECT In this case the wavefronts of a reference beam in conjunction with the beam of diffusely reflected light from a threedimensional scene is shown in Figure 2a. The relationships given in Eqs. Notice, as shown in Figure 8c, that the summation of the cosinic ray 1Re = 2Re2 is three times the radius Re of the largest cosinic circle. Assuming that without the corrective lens, the relaxed eye forms clear retinal images of faraway objects, the far point of the eye/corrective lens system will be at the position of the object whose image formed by the spectacle lens is faraway. The parallel rays emerging from the interferometer are brought to a focus by lens L2 at P, where the eye is placed. Now at Dnd , independent of y0 . One can shown that the irradiance in the second harmonic field is proportional to the irradiance factor sinc2 a ckL b2 where L is the distance into the crystal and k is the wave propagation constant, equal to nv>c. For example, an optical fiber transmitting at 1.3 mm rather than, say, 800 nm represents a seven-fold reduction in Rayleigh scattering losses. (57) and (58). The collimated region extends over two Rayleigh ranges, one on either side of the beam waist. (c) Formation of a conoidal image from a series of conoidal circles. We begin with an analysis of the irradiance profile of the Gaussian beam and then turn to an examination of the shape of the phase fronts associated with the beam. The crossover point of the curves coincides with the plasma frequency. If the interferometer components are of high quality, this system can M2 M2 L1 BS M1 BS S S P L2 P Figure 4(a) Twyman-Green interferometer. With the method used in Section 5 to derive the FabryPerot transmittance, find the reflectance, R = IR>I0 , of a Fabry-Perot cavity. Notice that the phase difference d is independent of the crystal length. Reading, MA: Addison-Wesley Publishing Company, 1968. Light output (typically given in lumens) depends both on the filament temperature and the electrical input power (wattage). The helium atoms receive their energy from free electrons via collisions. The relative phase between the two-wave field components is then determined by the phase factor eih = ei(vt - kz) The position and length of the image formed by the lens. Include the presence of a field of irradiance I removed with the 2-to-1 transition, the pump interaction, and the decay processes. Transparent materials like glass have resonance frequencies in the infrared and ultraviolet regions but not in the visible. The radius of the first 1n = 12 zone determines the magnitude of r0 , or the point P on the axis for which the configuration functions as a zone plate. What we have said here of a finite wave train is also true of any isolated pulse, regardless of its shape. One can then also define the angular field of view as twice the angle b made by the chief ray with the axis at the center of the opening represented by the entrance pupil. EM Waves in Thermal Equilibrium One of the early triumphs of quantum mechanics was the prediction of the experimentally verified relation giving the wavelength distribution (i.e., the spectrum) associated with electromagnetic radiation in thermal equilibrium with a blackbody at temperature T. A standard DWDM system might use 40 wavelength channels near 1550 nm. Of course, both n-type and p-type materials have zero net charge since the dopant atoms are neutral. The position of the aperture is critical in determining the magnitude of y2 and is least harmful in this respect when placed at the center of curvature, C. The individual slits are identified by the index j and the following expression for the resultant amplitude: 1>1j - 12a + bj>2 [12j - 12a + bj>2 B. I1Ae0 - vt2 N>2 BP = eikk sin u ds + eikk sin u ds f ae 0 (12j - 12a - b)2 j = 1 L1(12j - 12a + bj>2 (31) As j increases, pairs of slits symmetrically placed below (first integral) and above (second integral) the origin are included in the integration. 440 Chapter 20 Aberration Theory y a Wi da P a y a Ideal bz ud n2 Figure 2 Construction used to relate the ray aberrations by and bz to the wave aberration a. For a thin film in air, we are interested in the relative phase shift between rays reflected from the first surface (external) and the second surface (internal). 320 Chapter 13 Fresnel Diffraction 8 THE CORNU SPIRAL If we neglect the effect of the obliquity factor and the variation of the product rr0 in the denominator of Eq. (27), the Fresnel-Kirchhoff integral may be approximated by EP = C1e -ivt 0 eik1r + r0 2 dA (24) AP where all constants are coalesced into C1 . For this general case, the resultant field of Eq. (7) can be simplified by writing the fields in complex form and using a phasor diagram to aid in the addition of the individual fields. E = E0 sin 2p a - vt b x + E0 sin 2p a - vt byN l1 p B c. This is equivalent to the effective pump rate Rp1 feeds the population of level 1 and so increases the likelihood of stimulated absorption. How long can the coaxial cable be under these conditions? For visual observations, the intermediate image is made to occur at or just inside the first focal point fe of the eyepiece. This technique was employed by Michelson to measure the angular diameter of stars. The simplest explanation of these phenomena can be undertaken successfully by treating light as a wave motion. What are the displacement, velocity, and acceleration of a particle in the medium at x = 5 cm and t = 0.2? The point objects and the centers of their Airy discs are both separated by the angle u. If the equations are developed along the same lines, one finds that only a minor alteration of the transfer matrix becomes necessary. In the expression for q1 , Eq. (13), the cosine factor now appears in the denominator rather than in the numerator. If a thin plate of glass 1n = 1.502 of thickness 100 microns is placed over one of the slits, what is the lateral fringe displacement at the screen? If L is taken small enough, for example, the equation predicts a beam width less than b, contrary to assumption. To this, Fresnel added the assumption that the actual field at any point beyond the wavefront is a superposition of all these wavelets, taking into account both their amplitudes and phases. Solution E0 The ruling period d is twice the slit width, so d = 2 mm. These quantities will be seen to depend not only on the change in refractive index and the angle of incidence at the surface but also on the polarization of the incident light. Example 3 Light from a distant galaxy shows the characteristic lines of the oxygen spectrum, except that the wavelengths are shifted from their values as measured using laboratory sources. E = E013xN + 4yN 2eI1kz - vt2 B c. At the aperture, the wavefront sees 308 309 Fresnel Diffraction ds r0 O S r P is still substantially spherical, because the source is far away. By way of summary, we have discussed three ways of reducing pulse broadening in fibers: (1) use a single-mode fiber to eliminate modal distortion, (2) use a light source of small spectral width d to reduce material dispersion, and (3) use a light source operating in a spectral region where both attenuation and dispersion are as small as possible. Notice that these changes leave the first of the alternative forms invariant. TABLE 1 SUMMARY OF SOME SIMPLE RAY-TRANSFER MATRICES Translation matrix: M 1 L 0 1 P L Refraction matrix, spherical interface: R 1 M = n. Rn L n n n P n (R) : convex (R) : concave Refraction matrix, plane interface: M 1 0 0 n n R1 Thin-lens matrix: 1 M = N2 0 1 f 1 n = f n 1 1 R1 n n n n n (R) : convex (f) : concave Spherical mirror matrix M 1 0 2 R 1 R (R) : convex (R) : concave 2 SYSTEM RAY-TRANSFER MATRIX By combining appropriate individual matrices in the proper order, according to Eq. (14), it is possible to express any optical system by a single 2 * 2 matrix, which we call the system matrix. For the difference to be zero, that is, for destructive interference to be complete, the amplitudes must be equal. 345 Matrix Treatment of Polarization This particular choice, however, leads to a common form of the matrix, due to its symmetrical form: M = e -ip>4 0 0 ip>4 0 0 e c e ip>4 0 0 d (JWP, SA vertical) (17) In arriving at the last 2 * 2 matrix in Eq. (17), we used the relationship eip>4 + e ip>4 = eip>2. Schmidt designed a transparent correcting plate, to be placed at the aperture, whose function was to bring the focus of all zones to the same point on the spherical focal surface, as indicated in (c). Assume sodium light. Others conclusions produce some curious results, which can be verified experimentally. If I1 and I2 are known to be, for example, very near a nominal wavelength, l = 500 nm, this record can be used to accurately determine the difference in the two wavelengths. The power just inside the fiber exit is only 1 mW. The common orientation of the molecules in a liquid crystal allows the liquid crystal to interact differently with different polarizations of light passing through the crystal. Note that, for normal incidence, the reflection and transmission coefficients for the TE case are identical to those for the TM case. The rate of occurrence per unit volume of stimulated emission, RSt. Ifn , , when a wavelength dependent refractive index. Light is incident on an assembly of atoms like the one depicted in Figure 13a in RS. Em. = R21g(n)2I>c2N2 (10) The parameter B21 is the Einstein B coefficient for stimulated emission. Thicknesses are determined at l = 550 nm. Determine the position and size of the image in each case. The output mirror has transmittance T3 . As indicated in Figure 9b, such a voltage acts to align the molecules along the direction of the electric field between the glass plates. The radius of curvature of the convex surface of the lens is found from the lensmaker's equation: 1 1 1 + = n - 1 = f22 = 1216.25 = 2.502 = 4.375 cm The equivalent focal length is found from 1 1 1 1 1 4.375 + = + = + f1 f2 (12 f2) 6.25 2 50 16.2512 502 which gives f = 3.57 cm. These cases are described in the following subsections. In the hemisphere, the Gaussian laser has given information that is provided from these few gray-scale characteristics. In other words, the bandwidth is less precisely determined than the phase. Before and after they pass through the glass of decreasing thickness, a tilted region forms that is replaced by a large aberration of light, where in the glass, the other, the output is about the length of the fibers. As the laser operation was limited to a narrow frequency range at a higher power and in a distance, on the fast axis (x-direction), the light produced a fine pattern, which in the ideal situation is uniformly distributed along the circle (the ring) and the rings increase to higher rates. Since the law of refraction requires that refracted rays remain in the plane of incidence, a meridional ray remains within the meridional plane throughout its trajectory. Accordingly, rods bleach out completely at much lower light levels than do cones. These properties follow from the basic nature of the PC wave, as described earlier. Examination 381 am 2u 1 8n am Be 2 Holography 1m1 in Dne ut 1 xt 2 Cm Q P Cot 2n c Cs Cs 2u Cc 2 Cu 2 C1 C2 C2 C1 C2 C1 C2 C1 C2 G Gi G G G d of the right triangle POB in either of the constructions leads to the desired relation, 1 sin u = 2pr Thus, 1 0 = 2 sin u Thus, 1 0 = 2 sin u Thus, the number of grooves/cm is 2 sin1202 = 1. Cm s = m = o > x 56,790 grooves>cm d l l0>n 1488 * 10-7 cm2>1.6 6 OTHER APPLICATIONS OF HOLOGRAPHY Holography offers a wide variety of fascinating applications, of which we briefly describe only a few. T 2 Because the yellow sodium D line is a doublet (589.0 and 589.6 nm), the more monochromatic d line of helium at 587.56 nm is often preferred to characterize the center of the visible spectrum. From the geometry apparent in Figure 1, r2 = 1X - x22 + 1Y - y22 + 1Z - z22 and r0 = X2 + Y2 + Z2 so that r2 = r20 - 2xX - 2yY + 1x2 + y22 (10) Although the dimensions X and Y in the spectrum plane may be appreciable, the dimensions x and y are typically negligible in comparison with r0 for farfield diffraction. 10 BABINET'S PRINCIPLE Apertures like those of Figure 15 and 16, in which clear and opaque regions are simply reversed, are called complementary apertures. Thus, the focal length of the lens determines the spot size achieved when the beam is focused by the film and the corresponding image size. 4 How many lines must be ruled on a transmission grating so that it is just capable of resolving the sodium doublet (589.592 nm and 588.995 nm) in the first- and second-order spectra? 12 Light is incident upon an air-diamond interface. An examination of the four photographs shows that the principal maxima become narrower and secondary maxima begin to appear as the number of slits increases. Solution The optimum separation is given by L = 121l1 + f22 = 1216.25 + 2.50 2 = 17.5 cm. The amplitude at the point is found as in the following passage. The magnitudes of E for wave are given as: Then light waves shift both wave and particle, yet it was precisely neither. Let us assume a square magnification of l. For nearly monochromatic fields we typically say simply that vg is the frequency of the field. The character of the incident light will be unmodified by the plate, and so extinguished, if the phase difference introduced by the retarder is 2p or some multiple thereof so that the retardation plate functions as a full-wave plate. Of course, both conventions lead to the same physical result since the extra factor of -1 simply reverses the direction of the electric field reference arrow. 168 Chapter 6 Properties of Lasers The most important requirement of the amplifying medium is its ability to support a population inversion between two energy levels of the laser atoms. With the parameters for the laser system specified, one can use the ABCD propagation law to determine the location l and size of the beam waist w01/2 outside of the laser. Similarly, the field of view in image space can be described by a', the angle subtended by the exit window at the center of the exit pupil. All these features are exhibited qualitatively in the top diagram of Figure 23a. Examination of Eqs. Freeman and Company Publishers, 1958. Mirror Reflection Coefficient Coefficient of Finesse, F Finesse, F Quality Factor, Q Photon Lifetime, Tp (s) Resolving Power, R (Lmin (nm) FSR (Variable Spacing) (mm) FWHM (Variable Spacing) (mm) FSR (Variable Frequency) (GHz) FWHM (Variable Frequency) (GHz) r 4r2 11 - r222 pr 1 - r2 n F 1c>2d2 d c11 -22F 1d2 2dF 1>2 1F c 2d c 2dF 0.2 0.5 0.8 0.9 0.97 0.99 0.174 1.78 19.8 89.8 1080 9900 0.655 2.09 6.98 14.9 51.6 156 1.31 * 105 4.19 * 105 1.40 * 106 2.98 * 106 1.03 * 107 3.13 * 107 NA NA 4.63 * 10-10 8.77 * 10-10 2.82 * 10-9 8.38 * 10-9 1.31 * 105 4.19 * 105 1.40 * 106 2.98 * 106 1.03 * 107 3.13 * 107 8.02 * 10-3 1.19 * 10-3 3.58 * 10-4 1.68 * 10-4 4.85 * 10-5 1.60 * 10-5 250 250 250 250 250 250 NA NA 35.8 16.8 4.85 1.6 3 3 3 3 3 3 NA NA 0.43 0.202 0.0582 0.0192 10 GRAVITATIONAL WAVE DETECTORS We conclude this chapter with a description of interferometers used for gravitational wave detection. In a hydrogen atom there are eight distinct ways of combining the orbital and spin angular momentum of the electron to yield the same energy E2 . These may be spectrographs, which record a portion of the spectrum on a photographic plate, photodiode array, or other image detector, or spectrometers, where a narrow portion of the spectrum is allowed to pass through an exit slit onto a photomultiplier or other light detector. The applied electric field induces birefringence with an optic axis parallel to the applied field. (b) Figure 11 Soleil-Babinet compensator. Thus, using Eqs. If the image size, as in fact, is proportional to the focal length of the lens, so we can write Ee r a D 2 b (26) The quantity D/f is the relative aperture of the lens (also called f-number or f/stop), which we symbolize by the letter A. K F D (27) but is, unfortunately, usually identified by the symbol f/A. 273 Fraunhofer Diffraction The central maximum represents essentially the image of the slit on a distant screen. Rays of light corresponding to each wavelength component emerge mutually parallel after refraction by the prism and are viewed by a telescope focused for infinity. 194 Chapter 8 Optical Interferometry beams 2 and 3 can be gradually varied. 317 Fresnel Diffraction Example 1 If light of wavelength 632.8 nm illuminates a zone plate, what is the radius of the first zone radius relative to a point 30 cm from the zone plate on the central axis? The Fourier Transform and Its Applications to Optics, 2d ed. Thus, knowledge of the phase at point P1 at time t1 allows one to predict with confidence the phase of the field at this same time t1 at a spatially distinct point P2 along the same wavefront. Although prism materials of large n produce a large deviation at a given wavelength, the dispersion or separation of neighboring wavelengths need not be correspondingly large. 6 A circular disc of radius 20 cm and uniform luminance of 105 cd>m2 illuminates a small plane surface area of 1 cm2 , 1 m distant from the center of the disc. By now it may be apparent that in determining the resultant vibration due to two perpendicular components, we are in fact determining the appropriate Lissajous figure. These unit equations are developed following an approach taken by Albert Einstein in 1916. Thus, dn 1 = 6 21eV2 = 2pp 3 2p 3 2p Lcm = m0E1 = m V 10 0 where V = E1 is the voltage applied across the length L of the cell. Following the routine used in part (a), the linear susceptibility of b-carotene in ethanol is x1 = n2 = 1.32 = 1.69. The linear cavity case is complicated by the fact that the field encounters the gain medium twice in each round-trip with the losses encountered at the mirrors interspersed between passes through the gain medium. In the S surface, however, the image of the circle will not be sharp, having everywhere the width of the S focal line. At normal incidence, the transfer 484 Chapter 22 Theory of Multilayer Films matrix of a single film of quarter-wave thickness is M1 = J 0 ig1 ig1 K 0 The transfer matrix M for two such layers is found, according to Eq. (26), by forming the product M = M1M2 = J 0 ig1 ig1 K J 0 ig2 g2 ig2 K = B 0 -g1 g2 -g2 g1 R 0 -g1 g2 T Matrix components are m11 = -g2>g1 , m22 = -g1>g2 , and m12 = m21 = 0. A ray leaving the tip of the object and passing directly through the center of a converging or diverging lens, emerging unaltered, as in Figure 22a or 22b. Find the position and length of the line image formed by the lens for a point object 20 cm from the lens. Solid-state lasers typically have outputs with wavelengths in the near infrared. For first order, Eq. (5) requires knowledge of the diffraction angle u1 . 2d (n 1) ym (m S1 mld) s) 2d a (n 1) ym a 2 m s S2 d s Figure 9 Interference with Fresnel's biprism. The important parameters governing this type of pumping are the electron excitation cross sections and the lifetimes of the various energy levels. Modern Optics (New York: John Wiley and Sons, 1990, Ch. 9). Now recall that the phase difference of waves can be determined according to Eq. (10), that we can write the phase difference d = 2pd/ln = 72 (11) where n is the thickness of the film. 6 Calculate the far-field distance zFF = 50z0 for the externally focused beam waist. Then for the x3 term of the polarization to be 1% of the linear term, x3E 30 = 10.012x1E0 or, E0 = A 10.012 x1 1.69 = 10.012 10 V>m = 1.3 * 109 V>m x3 A 10 The corresponding irradiance is about I = 1 e0cnE 20 = 18.85 * 10-12213 * 108211.32 2 2 211.3 * 1092 V>m2 3 * 1015 W>m2 = 3 * 1011 W>cm2 = 300 W>mm2 Field strengths like these are easily achieved in pulsed lasers. 9 Using the technique of phasor diagrams, examine the combination of sharp irradiances at a different frequency. Since the net reflected irradiance vanishes, there is a perfect cancellation of the first beam with the sum of all the remaining beams. What should be the apex angle u, as in Figure 7? The analysis shows that the resultant is just another harmonic wave having the same frequency. In Figure 5, c is plotted as a function of x at fixed times t = 0 and several wavefronts associated with the plane sound wave are depicted at this same time. 3 POLARIZATION BY SCATTERING Before discussing the polarization of light that occurs in scattering, we make a slight detour to discuss scattering in general. Longer wavelength parts can cause unfavorable interfering. Portions of a square wave input pulse starting at point A arrive at the fiber end B at different times, depending on their paths. In a linear cavity, the loss modulation "gate" is placed near one of the mirrors and is switched to the low-loss state for a brief period once each round-trip. (56) and (57), together with the relation for the pulse repetition time T = 2n>c, leads to an approximate expression for the temporal width dp of a mode-locked pulse, dp = 2p/N(tf)2n>c2 PCWT 1 1 e — p Pin Pin Figure 13 The number of modes that are above threshold depends on the bandwidth ¢n of the gain medium and on the ratio of the small-signal gain coefficient to the threshold gain coefficient. Verify the reasonableness of your results by comparison with Figure 2. 472 Chapter 21 Fourier Optics S Input M1 D SP Output M2 Figure 11 Elements of a Michelson interferometer used as a Fourier-transform spectrometer. Determine the spatial coherence length for "good" coherence, neglecting any variations in brightness across the surface. The glass is of index 1.50. A sketch of one possible arrangement is shown in Figure 19. This sort of sensor is a common component of motion detectors. In this configuration, the liquid crystal does not alter the orientation of the vertical polarization of the light passing through the nematic cell and so the light is blocked by the action of the polarizer with a horizontal transmission axis. In the analysis that follows, we will make use of the notion of a propagation factor PF(z, z'). This has the effect of producing 50% transmission where V = 0 so that the operating point is located at P in the figure, rather than at the origin. For this film, Eq. (43) predicts a reflectance of 1.3% in the visible region, where the uncoated glass (not shown, n = 1.52) would reflect about 4.3%. Thus, for objects at a standard distance of 1000 yd, u = D/H = s L or h = su = 1000 yd * 0.00028 = 0.28 yd h u (in radians) = H>F (10) 2 5 Reflection Telescopes Larger-aperture objective lenses provide greater light-gathering power and resolution. That is, Pi = Pr + Pt (40) If we represent the reflectance R as the ratio of reflected to incident power and the transmittance T as the ratio of transmitted to incident power, R = Pr and T = Pt Pi (41) Then Eq. (40) takes the form 1 = R + T (42) The irradiance I is the power density (W>m2), so that we may write, in place of Eq. (40), IiA = IrA + ItA1 (43) Here, A is an area on the boundary plane, so that the cross-sectional areas of the three beams (see Figure 9) that appear in Eq. (43) are all related to the area A through the cosine factors. Fundamental properties of light are found by reasoning that the sensitivity of the beams in the boundary plane through the cosines of the angles of incidence, reflection, and refraction. 33. 1968): 59–70. Figure Credits Photo Sound: microphone Visual: video camera Data: computer Message Input Amplification Filtering Amplification 245 LEDILD Modulator Carrier source Analogidigital I. Cl Electrical Optic fiber glass Plastic Light Detector Attenuation and distortion PIN APD light electrical Signal processor Sound: loudspeaker Visual: CRT Data: computer Message output Amplification Filtering demodulation Figure 1 Overview of a fiber-optics communication system. As noted, reliable detection of gravitational waves would require isolating the interferometer from environmental noise and separating the gravitational signal from the remaining environmental noise signals. Solution Using Eqs. Solution Using Eq. (6) gives LC = 0.8 mm = 9.2 mm 14211.50191 - 1.48022 This calculation shows that the maximum crystal thickness useful in generating second harmonic light is typically quite small, in this case around 10 times the wavelength of the fundamental. For either the real image RI in (a) or the virtual image VI in (b), it follows that hi ho = s s¿ and lateral magnification [m] = hi ho = - s¿ s ho h In accordance with this sign convention adopted here, the magnification should be the negative of the ratio of the image to the object distances, since in case (a), s 7 0, s¿ 7 0, and m 6 0 because the image is inverted; in case (b), Figure 22 Ray diagrams for image formation by a convex lens (a) and a concave lens (b). Thus, if the distance DG is yit, a wavelet of radius yit is constructed with center at D. "Daylight" lamps, for example, use a mixture of zinc beryllium silicate and magnesium tungstate. By contrast, a hologram is made, as we shall see, without use of a lens or any other focusing device. Notice B that the force 1evB * B2 on the electron due to the magnetic field of B the radiation is omitted; it is, in fact, negligible compared with the force 1e E2 due to the electric field. In this section we discuss these processes and introduce the so-called Einstein A and B coefficients that govern their rates of occurrence. F = 1 cm Obj mo(obj) 25 cm Problem 31. The its contains two sets of slots at opposite ends of the bar the reflected irradiance of rays (a) in the transparent film, the direction of vibration is along the light ray. Even when such fibers are used, the propagation of light through them is generally not a straightforward matter. Show that a light spot formed by a lens placed at about 2 mm on a bright image of a spherical wave forms whose wavelength is about 1 m. Polaroid is not an ideal polarizer, not all the energy of the E-vibrations parallel to the TA are transmitted, nor are all E-vibrations perpendicular to the TA absorbed. (Figures 11b, c and d from M. The most far-reaching applications of fiber optics lie in the area of communications, the subject of the following section. Prefactors such as 2 and 2i may therefore be ignored unless information regarding energy is required. The fundamental limit of the laser linewidth arises from the fact that some of the randomly-phased spontaneous emission from the gain medium does exit the laser output mirror and, when mixed with the stimulated emission output, leads to a finite linewidth. (c) Diffraction image of a circular aperture. 6 Light rays enter the plane surface of a glass hemisphere of radius 5 cm and refractive index 1.5. s. Using a sketch, show that the irradiance of a given wavelength is the same for a given angle u, the light transmitted by the pair is given by I = a0b 0 cos2 u 2 b. Note that it leaves P, passes through M, the center of AS and EnP, undergoes refraction at L1 , heads for ExP, refracts again at L2 before reaching O¿P¿, and heads for O¿. The final image, at H, in addition, < w1, so that the Vene images are of the mirrors so long as the separation z p does not exceed the so-called coherence length, lt, of the source, (4) and (5). These instruments are discussed later. Figure 7b illustrates another arrangement, in which the source is a small point. Such an interference is extremely constructively, it follows that they will be formed when the wavefront propagates as such. Using Eqs. Kilger, David S. The etalon, being much shorter than the laser cavity, has a free spectral range, nfsr = c>2d, that is much larger than that of the laser cavity, c/2L. The three key rays discussed in connection with Figure 17 are chosen as the basis of the graphical ray-trace technique because, once the mirror center of curvature C, the focal point F, and the vertex V are known as such a straightedge device. This effect becomes increasingly important as the pulse width is reduced and the propagation length is increased, and so may be important in longhaul, high-bit-rate systems. 1 FRESNEL-KIRCHHOFF DIFFRACTION INTEGRAL A typical arrangement is shown in Figure 2. As the pinhole is reduced further, the images of each object point actually grow larger again due to diffraction, with consequent degradation of the image. 2f The magnification given by Eq. (33) is also valid for a double-lens eyepiece if the equivalent focal length given by Eq. (35) is used. The field lens then forms a real image (RI) that is viewed by the eye lens. We show that P also represents a certain measure of fringe contrast, written as the ratio 1IT2max - 1IT2min 1IT2min = Tmax - Tmin = 1IT2min Tmin (27) From the Airy formula, Eq. (26), T takes on its maximum value Tmax = 1 , when sin1d>22 = 0, and its minimum value Tmin = 1>11 + F2, when sin1d>22 = 1. F2 is the coefficient of finesse. The length of this part of the spectrum is the whole image. ln = 2 c c Figure 13 Specification of slit width and separation for double-slit diffraction. 0.5 C(y) 328 Chapter 13 Fresnel Diffraction Eq. (28), 2 y ez = ev = A L[A L] (39) Once Ls is calculated from Eq. (25), the contributing spiral-length interval y0 on the Cornu spiral can be determined. With the advent of the more intense and coherent light made available by the laser, we shall see that the optical properties of the medium, such as its refractive index, become a function of the electric field of the light. Writing Eq. (40) in the form c2 = 1 2 where nv2 = Nd 3 Nd 2 where N1 is the wave number, it follows that n1 is constant. The condition k = 2p is the same condition for reflected light as that for the m in the direction of the spot of the diffraction pattern. This means the image of an arbitrary point of the image plane at an arbitrary object plane is also a large number of total internal reflections. Equation (24) describes a beam propagating in the +z direction. f The eleventh bright ring of the 546-nm fringe system coincides with the tenth ring of the other, what is the second wavelength? Show that the error in the image of an object is being, in that of the spectrum with a sketch of the optical system, roughly to scale, and one from the optical system. Let us take the region of the object as having "a significant penetration" to be the depth L at which the irradiance of the diode has decreased to I>e 0.368 of its initial value. Any two rays are sufficient to locate the image; the third ray may be drawn as a check on the accuracy of the graphical trace. It is reasonable to set N0 1 NT for either of these irradiances? The strength of the binding of the outermost valence electrons is described by the band-gap energy, which is the energy required to free an electron from its host nucleus. The diameter of the focused spot is limited by lens aberrations and diffraction but can be roughly as small as the wavelength of the laser light. The preceding description does not explain why the velocities of the two components are so different. 4 For a pair of oppositely polarized modes shifted by a certain amount it differs at all. 1985: 54.) Refractive index nR 1.0 0.1 0.1 Extinction coefficient nI 1.0 nR 0.01 nI 1015 25 1016 1017 Frequency (rad/s) Optical Properties of Materials INTRODUCTION Electromagnetic waves that encounter materials create a complex of interactions with the charged particles of the medium. Let us suppose now (Figure 20b) that the second medium is only 10 cm thick, forming a thick lens, with a second, concave spherical surface, also of radius 5 cm. f 1 = f2 = f(l) = 1.54 f(l) = f2 f2 = 1.54 f(l) = 1.5 d = 20 d(2) = 20.001 Therefore, the image of the first-order maximum is less with a typical example. 100 cm-1. After equating real parts and imaginary parts, we sort out the unknowns w02 and Z2 in the following form: Z1 2 1 1 p w0 2 = a 1 + b b f 1 w02 w01 Z2 2 Z2 w02 f 2 + f f21Z1 - f2 1Z1 - f22 + pw2012>22 (46) (47) 600 Chapter 27 Characteristics of Laser Beams We see from Eq. (47) that for the general case, Z2 2 f. In general, whenever a train of reflecting or refracting surfaces is involved in the processing of a final image, the individual reflections and/or refractions are considered in turn, the image formed by one element serving as the object for the next. Whenever a beam of light is considered at... If the beams are argon-ion laser beams of wavelength 488 nm and the angle between beams is 120°, how many grooves per millimeter are formed in a plane emulsion 1n = 12 oriented perpendicular to the fringes? For the same wavelength, Ml = 2 ps>nm-km, giving a pulse broadening of 2/100 times as great, or only 40 ps/km. The ray is then simply the path along which light energy is transmitted from one point to another in an optical system. The requirement is met quite well using zirconium dioxide 1n2 = 2.12 and cerium trifluoride 1n1 = 1.652, both good coating materials. 4 Show that the relativistic momentum of an electron, accelerated through a potential difference of 1 million volts, can be conveniently expressed as 1.422 MeV/c, where c is the speed of light. Cancellation of b produces the desired relationship, 2 1 1 = s s¿ R (11) If the spherical surface is chosen to be concave instead, the center of curvature would be to the left. 7 VARIABLE-INPUT-FREQUENCY FABRY-PEROT INTERFEROMETERS For the scanning Fabry-Perot cavity discussed in the previous section, the transmittance through the Fabry-Perot cavity is a function of the changing length of the cavity. Figure 17a shows three Mach-Zehnder fiber interferometers (MZ1, MZ2, and MZ3) arranged to demultiplex a signal containing four distinct wavelength channels. Thus, the angular magnification for an image viewed at infinity is M = 25 feff (40) where feff (in cm) is the effective focal length of the two lenses, separated by a distance d, and given by Eq. (35). The object is 14 cm in front of the lens and the stop is 2.50 cm behind the lens. 14 Assume that the pupil diameter of a normal eye typically can vary from 2 to 7 mm in response to ambient light variations. condition for missing orders: a = a y ab m Thus, when the slit separation is an integral multiple of the slit width, the condition for missing orders is satisfied exactly for the interference maximum that coincides with the first diffraction minimum. The harmonic waves that go to make up the wave theory of light on a firm foundation, that foundation was to crumble as the century came to an end. When both sources act together, however, the fringe systems overlap. In ordinary fluorescent sources, light emitted by different points of a source, well over a wavelength in separation, is not correlated in phase and so lacks coherence. For internal reflection when light travels in the opposite direction, so that nt = 1.5 and ni2 = 1, up = 33.7°. The phase difference between waves from adjoining slits and in the direction of u can be found from Figure 5 by recalling that the angle a represents half the phase difference between rays. The detection of this ... (48) B 0B $ * E = 0t B (49) B $#B = 0 B B C¿ $ * B = (50) B 0E J + e0 0t (51) As before, $ * 1$ * E2 = - $2E because $ # E = 0 in the identity of Eq. (23). For some time this perplexing state of affairs, referred to as the wave-particle duality, provided the greatest scientific minds of our age to find a resolution to these apparently contradictory models of light. Results apply quite well also to cases of near-normal incidence. Equation (11) is equivalent to the two equations E0 = Er1 = m11Et2 + m12gsEt2 g0E0 - Er12 = m21Et2 + m22gsEt2 Dividing through these two equations by E0 and making use of the reflection coefficient r and transmission coefficient t, defined as r K Er1 E0 and t K Et2 E0 (32) we obtain 1 + r = m11t + m12gst (33) g0t1 - r2 = m21t + m22gst (34) 481 Theory of Multilayer Films Equations (33) and (34) can be solved for the transfer-matrix elements m given 1 + r = p0 + g0sgsm12 + gsm11 - g0m12 = gsm21 - g0m11 + g0sm22 + gsm12 (36) g0m11 (35) Equations (35) and (36), together with the transfer-matrix elements, defined by Eqs. If the lens aperture becomes too small to admit two such beams, such as (a) and (b) from S1 , no interference is detected. File breaking point values. 1 150 s¿ then with Eq. (37), AB = a 25 + 100 5 cm = 25 cm. Thermocouples and Thermopiles A thermocouple is a device in which an increase in the temperature at a junction of two dissimilar metals or semiconductors generates a voltage (Figure 1a). In 1900, at the very dawn of the twentieth century, Max Planck announced at a meeting of the German Physical Society that he was able to derive the correct blackbody radiation spectrum only by assuming that atoms emitted light in discrete energy chunks rather than in a continuous manner. It should be pointed out that if the function to be represented is a function of spatial position x with period L, say, rather than of time t with g(x) and cn c1 c2 g(x) c3 v Figure 4 Fourier coefficients of a periodic function specify the harmonic components of the amplitude of at frequency vn . Determine the spot size at the beam waist, w0. We see that the elliptical shape of the incident light is not preserved, leading to the development of a signal that is fabricated in fabricating devices that behave as linear polarizers as well as in producing phase retarders such as QWPs, considered earlier in this chapter. Figure 3 shown the intermediate and final images produced by a two-lens system such as can be sketched in Figure 23a. In fact, the analysis holds for any sort of harmonic wave (e.g., spherical, cylindrical, or Gaussian). 522 Chapter 24 Nonlinear Optics and the Modulation of Light Horizontally polarized beam HR mirror Glan-laser prism Laser rod Pockels crystal (a) VHW Horizontally polarized beam Figure 6 Light-controlling action of a Pockels cell, used as a Q-switch. The electric field E in Eq. (6) should represent Bthe actual field at the dipole, in the interior of the B medium. Instead of a discrete spectrum of frequencies, as given by the Fourier series, Eq. (6), we are led to a continuous spectrum, as given by Eq. (8). When no distortions appear in the plane wavefronts through the interferometer, uniform illumination is seen near P. The surface charge density appears because each bilayer is not possible there. The isolator consists of a Faraday rotator situated between a polarizer-analyzer pair. Visual Optics and Refraction, 2d ed. 20 A 10-slit aperture, with slit spacing five times the slit width of 1 * 10-4 cm, is used to produce a Fraunhofer diffraction pattern with light of 435.8 nm. 352 Chapter 15 Production of Polarized Light the metal wires that operate as a dichroic polarizer. c. generated by this detector when an electromagnetic field of irradiance of 1 mW and wavelength 1.5 mm is incident on the detector? Determine the spacing of the developed silver planes within the emulsion. Bifocals, in which lenses of different powers are situated in the upper and lower half of a spectacle frame, can restore, to the presbyopic eye, clear vision of both near and distant objects. Notice that we have assumed a response time of w = 0, for applications requiring a large number of pixels, the number of wires required by such a design becomes unwieldy. B Figure 5 Resultant E-vibration due to orthogonal component vibrations of equal amplitude and phase difference of p>2, shown at three different times. Atoms in Thermal Equilibrium: The Boltzmann Distribution Consider an assembly of atoms in thermal equilibrium at temperature T. It may be manipulated by a lens, for example, in the same way as the original wavefront. If the fringe systems overlap with their maxima and minima falling together, the resulting fringe pattern is highly visible, and the radiation from the two incoherent sources is considered highly coherent. When the fringe systems are relatively displaced, however, the visibility of the resulting fringe pattern decreases. At greater separation, the composite pattern is not visible and the radiation is considered incoherent. Screen Lens Film 1 546 nm 0.2 mm Collimated beam 0.1 mm 1 mm Figure 21 1 C A m 12 8 p D 2 b. As another example, suppose the aperture function is a television picture in which horizontal raster lines are visible. Thus such structures can be designed as band-pass filters with high spectral transmittance in the wide region of low spectral reflectance. (b) Destructive interference: E1 and E2 differ in phase by p and the amplitude of the resultant wave is the difference in the amplitudes of E1 and E2 . What is the transmission of the system. 5 OPTICAL DISPLAYS In this section we describe briefly three different technologies used to display optical images in computer and TV monitors. denominator expresses the distance at which the smallest readable letter subtends 5¿ of arc overall. For = 0°, s' = 3.180 cm and ' = -23.51°; for = -20°, s' = 16.104 cm and ' = 6.081° 22. "How Light Interacts with Matter." In Lasers and Light, pp. It is this property of temporal coherence that is measured by the Michelson interferometer. If a laser source is used, the lenses may not be needed. Show that a small change in angle d to around the direction of minimum deviation, 60°, to obtain more. The laser medium are in the ground state. If N fringes are counted as the pressure in the cell changes from vacuum to atmospheric pressure, what is the index of refraction n in terms of N, l, and L? Rearranging Eq. (20), we identify the distance r0 as the first focal length f1 , given by f1 = R21 , l n = 1 (21) There are other focal points as well. The predominant frequencies in the Stokes and anti-Stokes fields are characteristic of the molecule and so their detection can be used to determine the composition of, for example, the gases in a particular combustion process. Light of wavelength 1 1IA = 1588 with very nearly satisfies the constructive interference condition (Eq. (22)) for output 2 since 1/11 = 11 11, 12 1/23 ,1 3 4 , 11 1 AZ2 21 14 M21 13 12 4 M23 /a) ,1l 11 ,1 2 3 4 M21 11 1 11 1 2 1 4 M23 1 11 ,1 Figure 17 Array of Mach-Zehnder fiber interferometers used to demultiplex a signal into four wavelength channels and (b) multiplex four wavelength channels into a signal. Example 5 A microscope has an objective of 3.8-mm focal length and an eyepiece of 30-mm focal length with a tube length of 20 cm and a typical eyepiece magnification of 10 ×. In general, a vector C b b is expressed in normalized form with B Figure 2 Representation of E-vectors of linearly polarized light with various orientations. (b) Fourier transform power spectrum for the image. This means that a beam distorted by passing through an optical system with severe aberrations can be recovered by "reflection" from a PCM that sends it back through the same system. In a recent advancement, the Figure 8 Correcting myopia by reshaping the cornea with radial keratotomy. The distance between slits is 0.005 mm and the slit width is 0.001 mm for each case. OPN Trends, "The Nature of Light: What is a Photon?" Vol. Nevertheless, if we call g the optical-path difference given by Eq. (35) and e the equivalent path difference arising from phase change on reflection, we can state general expressions the conditions for p p + e = m l (36) g p + e = m + 12 B l (37) constructive interference destructive interference: where m = 0, 1, 2, A . In geometrical optics, where light waves are treated as rays propagating along straight lines, we expect to see a sharp image of the aperture. As a result, light of orthogonal linear polarizations travels with different speeds through such a fiber. However, in the general case, for which C1 and C2 are not equal to zero, Eq. (62) remains the general solution for the field in a tunnel shared with a distributed set of detectors. Although this case might correspond to scattering of an incident beam from a distant star, the most likely explanation is the polarization of light as just described, as light is distributed over increasingly larger areas, producing an irradiance that decreases inversely with the square of the distance. The detailed lines within a letter, such as the vertical bar in the letter F or the horizontal bar in the letter H, are all constructed so that the width of each "bar" subtends an angle of 1¿ of arc at the location of the eye. Glass Figure 28 Problem 19. Optical Filtering We have seen that the back focal plane of the transform lens is the spectrum plane in which a Fourier transform of the aperture or transmittance function is located. 7 DISTORTION Light transmitted by a fiber may not only lose power by absorption and scattering but may also suffer distortion due to the broadening of the light pulses by the mechanisms just mentioned; it may also lose information through pulse broadening. The abbreviations read as follows: M.F.P. = myopic far point; N.N.P. = normal near point; M.N.P. = myopic near point. Solution For this interface, uc = sin-1 a 1 b = 38.7° 1.6 up = tan-11.62 = 58.0° up = tan-1 a 1 b = 32.0° 1.6 Since the angle of incidence of 30° is less than either upe or uc , Eqs. UV-B radiation has been linked to a variety of skin cancers and contributes to the sunburning process. Interference maxima are separated by 1.29 mm. 15 Consider the Fabry-Perot cavity shown in Figure 8. To compensate for off-axis wavelengths of once, a compensator plate C made of the same material and dimensions as BS is inserted parallel to BS in the path of beam 2. 64 Chapter 3 Optical Instrumentation TABLE 2 FRAUNHOFER LINES n (nm) 486.1 589.2 656.3 Characteristics Crown glass Flint glass F: blue D: yellow C: red 1.5286 1.5230 1.5205 1.7328 1.7205 1.7076 sodium atoms in the sun's outer atmosphere. 2 Using the thin prism at minimum deviation for D line, for example, the ratio of angular dispersion to deviation defines the dispersive power of the prism that d and Y' the d wavelengths to the deviation of the D wavelength, as suggested in Figure 13, is nF nC D = nD 1 - d D . This measure of the ratio of dispersion ¢ to deviation d is defined as the dispersive power of the prism is given by D = 1 >> ... for the thin prism. Table 3 ... respectively. These fields are described by the same coefficients, and the physical implications of Eq. (15) may be summarized as follows: The reference light is ... (11) and (12). Shown in Figure 7 (a) and (b) ... Eqs. 6 Discuss the physical implications of Eq. (15). Compare these results to those obtained in parts (d) and (e). (a) What power contact lens should an optometrist prescribe to move the myopic far point out to infinity? On this basis, double refraction in calcite could be understood as a phenomenon involving polarized light. While normal vision is 20/20, visual acuity readings as good as 20/15 are not uncommon. R2n = a r0 + Rn b2 2 b - r20 2 (19) which can be written as rn ½ = q a 1 2 r0 R2n + r20 n = a b 1 2 r0 b a 4 b r0 0 P Figure 8 Schematic for the calculation of Fresnel zone plate radii. Princeton, NJ: D. The order number for a 1-m Fabry-Perot interferometer in this case is very large and so typically in the range 105 – 106. How many fringes would be counted if the gas were carbon dioxide 1n = 1.000450 for a 10-cm cell length, using sodium light at 589 nm? ABCD Law With the correspondence between R(z) and q(z) established, we can, with the help of matrix methods, develop a simple, yet powerful, recipe for laser-beam propagation through an arbitrary optical system. 1 POLARIZATION OF A DIELECTRIC MEDIUM We take as our model an isotropic dielectric medium, that is, a nonconducting material whose properties are isotropic. Consequently, in the approach to steady state, the laser system undergoes relaxation oscillations that are damped and produce pulses that have peak irradiances far larger than the steady-state irradiance. A collimated beam of light of 1 111 112 112 11 (a) Achromatic prism (b) Direct-vision prism for wavelength l Figure 16 Nondispersive and nondeviating prisms. A ray leaving the tip of the object, parallel to the optical axis, undergoes refraction at the lens surfaces and passing through the right focal point F of a converging lens, as in Figure 22a. In each case, ER = E1 + E2 . For such a case, in the region outside the small Airy disc, Eu = 0, essentially. This bending of light waves around the edges of an obstruction came to be called diffraction. The cavity mirrors shown are separated by distance d. If, for example, a bright source is placed at the second focal point F in the Fabry-Perot cavity and one wishes to know the image position... The electric field at the cavity end is given. For the cavity mirrors, the light returning toward the cavity and thence to its origin, having passed through the cavity ... at points, S1 ... 260 Chapter 10 Fiber Optics Figure 14 Symbolic representation of waveguide dispersion. y1z, t2 = A sin12p[x1>l + z/m2 2. If the focal length of the lens representing the eyepiece is 4 cm, determine the focal length of the other. ¹2 Show that for substitution of E1x, y, z, t2 = U1x, y, z2eivt into the wave equation (3) leads to Eq. (7). This difference represents a significant saving of light energy in an optical system with multiple surfaces occurring between S and P. This interference pattern at the image, located at point S, has a pattern that depends on the position of the lens. Given the values of the parameters, find the electric field, using Eq. (14). 4 For the system of two lenses in Figure 13 with focal lengths of 8 cm and 18 cm, and spaced 12 cm apart, the final image formed by the system is located ... What happens to the image if the object is moved? 2 Show that a series expansion of the irradiance results in two equal contributions, one from each of the two orthogonal polarized components. 12 If the two coherent sources, separated by a distance, are fixed, determine the fringe separation. The interference pattern thus produced by the superposition of light from an extended source ... Show that an electromagnetic wave can be represented as a superposition of the two orthogonal polarizations, and that the resulting fields satisfy the wave equation. In a sense, the Jones vector method is similar to describing a light wave by two orthogonal components ... may be considered as well. In the special case of isotropic media ... The transmitted beam through the Fabry-Perot interferometer ... Thus, the reflection coefficient and transmission coefficients in the two-mirror cavity are related to ... The light with frequency in the transmission band is then reflected back toward the mirror ... 3 Show that the phase velocity of the wave ... Assume a refractive index of 1.5 for the glass. 2 (a) Given the expressions for the reflection coefficients, derive the reflectance ... Using Eqs. (14) and (15), find the polarization of the beam ... (a) What is the theoretical limit for the thickness of the plate? The amplitudes of the transmitted and reflected waves in terms of the incident amplitude are found ... For both polarizations we find, in the paraxial approximation, that both the lateral and longitudinal magnification are given ... This has the effect of the phase change of p on reflection ... The incident beam is split at the first surface into the reflected and transmitted beams ... A device with these properties ... The shadows observed formed a complex ... Fresnel's equations (41) and (42) ... 1 Determine the conditions for which the reflected ray is polarized, the direction of vibration is along the light ray. The Hertz-type wave, 1888, and the electric and magnetic fields ... In a case like this the lens may be treated ... Show the resulting position of a focused spot ... Note that Eq. (14) may be written in several ways ... The system as given is not consistent with the previous results ... Hence, the expression for the field is ... 2 3 5 7 9 ... Figure 20 shows the system. (a) Show that the electric field in the beam ... The derivation leads to an important conclusion: ... edge of the field of view is to be sharply delineated, the field stop should be placed in an image plane so that it is sharply focused along with the final image. The "shadows" observed formed a complex interference pattern like those produced with water waves. PROBLEMS 1 a. We may give physical significance to b by interpreting it as a phase difference. The resulting hologram is called a matched filter or a Vander Lugt filter, after its originator. The sinc function has the property that it approaches 1 as its argument approaches 0: lim sinc1b2 = lim a b:0 b:0 sin b b b = 1 b (11) Otherwise, the zeros of sinc1b2 occur when sin b = 0, that is, when b = 121kb sin u2 = mp m = ; 1, ; 2, Á Equation (11) shows that the value m = 0 should not be included in this condition. The closeness of the wavelengths for minimum absorption and minimum dispersion has motivated attempts to satisfy both conditions by shifting the dispersion curve towards longer wavelengths, so that it passes through zero at 1.55 mm instead of 1.31 mm. The fundamental wave equation for electromagnetic waves in the dielectric is a consequence of the Maxwell equations. Note that, in general, s represents the distance along a waveform measured along a direction that is perpendicular to the wavefronts associated with the wave. Let us assume the incident light consists of plane harmonic waves, expressed by B B B # B E = E0ei1k r - vt2 (1) B where the origin of coordinates is taken to be point O. Solid-state lasers are typically flash-lamp pulsed or optically pumped by 577 Laser Operation another laser. If point A¿ is constructed on the perpendicular AO such that AO = OA¿, the right triangles AOC and A¿OC are equal. All rays from the distant object point that pass through the zone form the comatic circle shown. New York: John Wiley and Sons, 1979. By Snell's law, n0 sin ut = nf sin ut (30) In addition, by inspection, AE = AG sin ut = a AC b sin ut 2 (31) and AD = AC sin ui (32) From Eq. (31) and incorporating, in turn, Eqs. Example 3 We illustrate case 3 in this example. Filled circles indicate electrons and empty circles indicate holes. Notice then that, except for the sign of the vt term, the reflected wave is the complex conjugate of the original wave and has the properties of a phase conjugate wave as described above: It retraces the path of the incident beam and is its phase-reversed replica. The wave description of light will be found adequate to describe most of the optical phenomena we cover. Consider the multiple reflections of the narrow beam of light of amplitude E0 and angle of incidence ui , as shown in Figure 22. The object distance for the second surface takes into account the thickness of the lens. Larger irradiances occur for gain media with larger saturation irradiances. (Adapted with permission from Mathew Alpern, "The Eyes and Vision," Section 12 in Handbook of Optics, New York: McGraw-Hill, 1978.) 6.96 mm 3.6 mm 7.2 mm N S3 F VC 425 Optics of the Eye TABLE 2 CONSTANTS OF A SCHEMATIC EYE Optical surface or element Cornea Lens (unit) Front surface Back surface Eye (unit) Front focal plane Back focal plane Front principal plane Back principal plane Front nodal plane Back nodal plane Anterior chamber Vitreous chamber Entrance pupil Exit pupil Defining symbol Distance from corneal vertex (mm) Radius of curvature of surface (mm) Refractive index Refractive power (diopters) S1 L S2 S3 — F F¿ H H¿ N N¿ AC VC EnP ExP — — +3.6 +7.2 — - 13.04 + 22.38 + 1.96 + 2.38 + 6.96 + 7.38 — — +3.04 +3.72 +8a — +10b -6 — — — — — — — — — — — — — 1.45 — — — — — — — — — 1.333 1.333 — — +41.6 +30.5 +12.3 + 20.5 + 66.6 — — — — — — — — — — — a The cornea is assumed to be infinitely thin. The shield helps to reflect light from the flashlamp back into the ruby rod. Following the pivotal work of James Clerk Maxwell, for whom the equations that govern electricity and magnetism are named, "light" is identified as an electromagnetic wave having a frequency in the range that human eyes can detect and interpret. After the resin has hardened, the replica grating can be separated from the master. Note that, for such a situation, the product function r1n2g1n2 is significant only over the range of frequencies near n0 for which g1n2 is significant. Some of the irradiance patterns for low values of the Hermite integers m and n—predictable from Eq. (68) and Figure 15—are reproduced in Figure 16. We now show that the minimum resolvable wavelength difference, ¢lmin , can be compactly expressed in terms of the cavity finesse F. Chromatic aberration and the five monochromatic aberrations (spherical aberration, coma, astigmatism, curvature of field, and distortion) occur largely as a result of the form and shape of lenses and mirrors and as a result of 59 Optical Instrumentation L2 A AS, EnP ExP P 3 cm Chief L1 L2 f1 6 cm ray f 2 10 cm 1.5 cm M N O 3 cm O O F1 F1, F2 F2 P P 3 cm 4 cm 12 cm 10 cm 18 cm 9 cm Figure 5 Solution to Example 1 (d). Cambridge: Cambridge University Press, 1997. As magnifications increase and the focal lengths and diameters of the objective lenses decrease corespondingly, the solid angle of useful rays from the object also decreases. Use the root-mean-square velocity of a gas molecule given by yrms = where R is the gas constant, T the Kelvin temperature, and M the molecular weight. Would a ratio of a>b = 9 fit the pattern shown?) Evidently, when a = Nb and N is large, the first missing order at p = ; N is far from the center of the pattern. With Eq. (21) for the Rayleigh range and the aperture diameter criterion D = 4.5w, one can calculate the Rayleigh range z0 for typical lasers as a function of aperture diameter. The optometrist would prescribe a contact 1 1 lens with a power of P = = = - 1.00 diopter 1-1.00 D2. The input is mercury green light of 546.1 nm. The coherence length lt of a wave train is the length of its coherent pulse, or lt = ct0 (16) Combining Eqs. Ch. 6. Show that, for this case and for g0 W gth , essentially every pump event leads to an output photon. Only those waves that satisfy a resonance condition are sustained. Shurcliff, Polarized Light: Production and Use (Cambridge, Mass.: Harvard University Press, 1962). Saleh, B. Important features of Eq. (25) to be discussed in the following paragraphs and the next subsection are shown in Figure 2. Image inversion may also be achieved without additional length, as in binoculars, through the use of inverting Porro prisms, discussed previously. This criterion is explained and used in the later treatment of diffraction, where it is shown that the minimum separation ¢a of the two wavefronts, such that the images formed are just barely resolvable, is given by ¢a = l d (22) Combining Eqs. The former face is on the left in contact with air and the other in contact with a liquid of index 1.4. The refractive index of the glass is 1.50. Incident on plane side: 8 cm beyond lens; on curved side: 5.33 cm beyond lens 34. For the responsivity to be a useful specification of a detector, it should be constant over the useful range of the instrument. 6 OPTICAL PHASE CONJUGATION Optical phase conjugation (OPC) represents another third-order, nonlinear phenomenon with some fascinating applications. for 20/300; 0.436 in. The device is hermetically sealed in an optically centered package. The phase velocity of an electromagnetic signal is a measure of the velocity of the harmonic waves that constitute the signal. The factor of 50 accounts for the approximately 50 round-trips made by the light in the Fabry-Perot cavities in each interferometer arm. and the factor 2 accounts for the fact that the light traverses the length of an arm twice in one roundtrip through the Fabry-Perot cavity in that arm. The presence of illumination and the extra free-charge carriers so produced effectively lower the resistance of the material, and a larger photocurrent results. In practice, the limit is around 1.6. The numerical aperture is an alternative means of defining a relative aperture or of describing how "fast" a lens is. 6 A reflecting telescope uses a spherical mirror with a 3-m focal length and an aperture given by f/3.75. The opacity, in turn, is just the reciprocal of the transmittance, T. The curves have been normalized to the same maximum amplitude. Inside the lens, therefore, rays are directed as before to form an image 40 cm to the right of the first surface. Approximately midway between S and T, the focus will be circular, the circle of least confusion. (a) product (c) 32.8%; 0.48 (a) 5 units of amplitude (c) 25[1 + sin(ay)]2 (A2 /) cos() (a) 18.3 kHz (b) 17.2 Hz (a) 0.04 Å (b) 0.1 Å (a) 2.86 × 10−3 cm (b) 5.59 nm (c) 224 nm (d) 0.80 reading/s 11. This anisotropy can be introduced by manufacturing fibers with elliptical cores or by applying an anisotropic stress to the fiber. However, for gain cells that are long enough to allow the irradiance to grow to an appreciable fraction of the saturation irradiance, the output irradiance is less for cells with smaller saturation irradiances. The final drawing, based on an original scale of 1 cm = 14 in., with all items of interest, is shown in Figure 5. Eye Beam splitter referred to as Haidinger fringes, or fringes of equal inclination, since they are formed by parallel incident beams from an extended source. In these cases, the resulting geometric relationship analogous to Eq. (11) consists of terms that are all positive. These two laws are summarized in Figure 1, which depicts the general case in which an incident ray is partially reflected and partially transmitted at a plane interface separating two transparent media. Courtesy of LIGO Laboratory. Structures and cavities inside can be revealed in three-dimensional images formed by ultrasonic holography. Solution a. (The irradiance of the sun at the earth's surface is about 1000 W>m2.) 20 For a Nd:YAG laser, there are four pump levels located at 1.53 eV, 1.653 eV, 2.119 eV, and 2.361 eV above the ground state energy level. The inevitable blur that diffraction produces in the image restricts the resolution of the instrument, that is, its ability to provide distinct images for distinct object points, either physically close together (as in a microscope) or separated by a small angle at the lens (as in a telescope). We wish to express the electric field ET transmitted through the FabryPerot interferometer in terms of the field EI incident on the interferometer, the reflection coefficient r of the cavity mirrors, and the length d of the cavity. A phasor diagram for the amplitude terms of Eq. (14) is shown in Figure 5a, as each Fresnel zone contribution an is added. Also, change the value of n to produce graphs for the case of external and internal reflection from diamond 1n = 2.422. That is, for an electromagnetic field waveform to be a mode of an optical cavity, it must have the same spatial form after one round-trip that it had at the start of the round-trip. If the applied electric field, or P E0 P0 E0 E P0 Figure 1 Linear and typical nonlinear response of polarization P to an applied electric field E. Plot the laser output irradiance as a function of the variable transmittance T3 of the output mirror. 7 A polished surface is examined using a Michelson interferometer with the polished surface replacing one of the mirrors. This design is used for large concave gratings, whereby the slit, grating, and plate holder all lie on a circle called the Rowland circle that has the following property. C = 0. Variables in the situation include the size and spectral width of the source and the shape and reflectance of the film. D. Determine the position and size of the entrance and exit pupils, as well as the image. Sketch the power spectrum, locating its zeros, and show that the frequency bandwidth for the pulse is inversely proportional to its duration. In the case of a perfect optical system, there is established a one-to-one correspondence between conjugate object and image points. We define reflection and transmission coefficients2 by r = Er , Ei t = Et Ei (41) 2 We will have occasion later to also use reflectance (R) and transmittance (T), defined as the ratio of the corresponding irradiances. The high resolution is gained at the expense of a contracted spectral range of only l>m = 755>30 = 25 nm. The two parts are superimposed again after traveling along different paths. Example 2 Estimate the coefficient of finesse F, the finesse F, and the mirror reflectivity r for a Fabry-Perot cavity with the transmittance curve shown in Figure 10. For example, taking n = 10,000, l = 600 nm, and r0 = 30 cm, one finds nl>r0 = 0.02 and n2 l 2 a b = 0.0001, justifying the neglect of the second term in the square 4 r0 brackets. It can be shown that this approximation does not affect the results of third-order aberration theory. By reducing the convergence with a number of diverging lenses placed in front of the eye, and so with a bigger focal length, an optometrist can determine the best diopter specification of the single corrective lens needed by simply adding the diopters of these test lenses. From Eq. (22) kY = 2p>l . Further, Fig. 9 shows the optic nerve on the axis of 3.33 cm in front of the lens, with an aperture of 3.33 cm; image is 10 cm behind the lens, inverted and 2 cm long. One criterion for broadly classifying interferometers distinguishes the manner in which the initial beam is separated. Ch. 2. In thermal equilibrium the rates of change of the 1 for, for example, M. Such materials manifest appreciable contributions to their optical properties from both free and bound charges and accordingly must be treated by allowing for both types of behavior. In the ultraviolet range of 110 to 160 nm, coatings of magnesium fluoride or lithium fluoride over aluminum are generally used to enhance reflectivity. See Table 1. Making only rough estimates, we shall ignore the fact that the wavefronts striking the lens from nearby object points A and B are not plane, as required in far-field 281 Fraunhofer Diffraction A Radius of Airy disk Usmin Example B Figure 11 Minimum angular resolution of a microscope. Such objectives are chromatically corrected, usually for the Fraunhofer C (red) and F (blue) wavelengths, and spherically corrected, at the Fraunhofer D (sodium yellow) wavelength. For each of these, the electric and the magnetic fields are... The end result consists of left- and right-circular components at 45° to each other whose superposition, upon emerging from the Faraday rotator, is linearly polarized light with its plane of polarization rotated relative to its original orientation. C P M (a) M BS M C F M (b) l Figure 7 (a) Michelson system for producing interference gratings, including collimator C, mirror M, and photographic plate P. Thus, the inner details of these cosmetic circles are not visible and all that is seen is the comblike cosmatic shape. Mill Valley, CA: University Science Books, 1986. (d) Active cavity containing a gain medium. (b) Transmittance for laser cavity of length l (solid curve) and etalon of length d (dashed curve). 129 Superposition of Waves different harmonic components. (a) Photovoltaic mode. The width of the spectral lines is a direct indication of the lifetime of the upper level of the transition. Determine, using Jones matrices, the character of the light after passing through (a) the QWP and (b) the final linear polarizer. In a Michelson interferometer, the differential length change ¢L in the arms of the interferometer leads to a change in the phase difference of the two beams coming from the interferometer arms and arriving at the detector. Figure 10b shows the gain coefficient at a time in the buildup to steady state when only four cavity modes remain above threshold. The optic nerve is the main trunk line that carries visual information from the retina to the brain, completing the remarkable process of vision. Concave-grating instruments are used for wavelengths in the soft X-ray (1 to 25 nm) and ultraviolet regions, extending into the visible. (Radiometric quantities are sometimes subscripted with the letter e. The penetration depth is given by Eq. (50): [formula illegible] (-) 326 Chapter 23 Fresnel Equations 6 COMPLEX REFRACTIVE INDEX We wish now to show that when the reflecting surface is metallic, the Fresnel equations we have derived continue to be valid, with one important modification. The index of refraction becomes a complex number, including an imaginary part that is an indication of the absorption of the wave. In the former case, then, let sn = -p>4 and e = -p>4. 79 Optical Instrumentation 4 MICROSCOPES The magnification of small objects accomplished by the simple magnifier is increased further by the compound microscope. The cones cluster preferentially near the center of the retina, a 3-mm-diameter region called the macula. 1 MATHEMATICAL REPRESENTATION OF POLARIZED LIGHT: JONES VECTORS Consider an electromagnetic wave propagating along the z-direction of the coordinate system shown in Figure 1. The brain records the message seen by the dominant eye, while suppressing the other. Calculate the difference in the refractive indices for the two rays in the crystal, assuming this to be the minimum thickness showing the effect for a wavelength of 600 nm. The objective of the telescope is a 50-cm positive lens, with a diameter of 4.50 cm. We begin with an argument owing to Sir George Stokes, which yields information concerning the amplitudes of reflected and transmitted portions of a plane wavefront incident on a plane refracting surface, as in Figure 21a. 14 A so-called "rabbit-ears" TV antenna is made of a pair of adjustable rods that can spread apart at different angles. 7 Reference to Table 2 indicates that the corneal radius of curvature for the unaccommodated schematic eye is 8 mm. The first two are traceable, for the most part, to an abnormally shaped eyeball, axially too long or too short. A LED is a solid-state device employing a p-n junction in a semiconducting crystal. In this case the emerging rays determine a virtual image VI near the object BO erect and slightly magnified. 14 Why should one expect laser light to be more difficult to attain than laser light at infrared wavelengths? After coming to a focus at I, the light rays continue to the eyepiece, or ocular lens. The discussion begins with an introduction to the operation of stops, pupils, and windows, of great practical importance to light control in optical instrumentation. There are also periodic times when the standing wave is everywhere zero, since cos vt = 0 for t = T>4, 3T>4, A . For a given plate, the right side of Eq. (11) is constant throughout the optical region of the spectrum, if the small variation 1n - n ß2 is neglected. For example, 2t the Jones vector C 2 D represents right-circularly polarized light since E0y E0x = E0y = E0x (a) E0y E0x E0y + E0x 2i i 1 d = 2 c d = 2i c d 2 1 c d The Jones vector may also reflect the amplitude and, hence, the irradiance of the light but not the polarization mode. The high-index material is encountered first by the incident light, as in Figure 8. This complication is explored in problem 28. Assume that the Fabry-Perot cavity used has a length of 10 cm and that the nominal frequency of the laser input is 4.53 * 1014 Hz. Find a. Thus, the surfaces of constant phase are a family of planes perpendicular to the x-axis. Screen Ocular Figure 39 s = where nc is the linear magnification of the ocular and s- is the distance from the ocular to the final image. In subsequent sections of this chapter, we examine so-called magneto-optic and acousto-optic devices. 2 The fourier series for the periodic sequence of two matrices and an arbitrarily large number of matrices. It is often described in terms of temporal coherence, which is a measure of the degree of monochromaticity of the light, and spatial coherence, which is a measure of the uniformity of phase across the optical wavefront. Solution We sketch the solution in outline form only. If point O in Figure 3 is the origin of secondary wavelets that arrive at an arbitrary point P in the field, then the correct modification of amplitude as a function of the angle u is given by u = a a0 b 11 + cos u2 2 (13) where the obliquity factor is normalized to unity in the forward direction, u = 0. Because the square of the displacement of the wave at any time is a measure of its irradiance, the energy delivered by the traveling sequence of pulses in Figure 7b is itself pulsating at a beat frequency, vb . Assume that the index of refraction of the fiber is n = 1.500. In one mode of operation, the lengths of the arms of the interferometer, in the absence of a signal, are adjusted so that destructive interference occurs at the detector. The electronic pulses corresponding to the photo-induced charge accumulated near each pixel in a given row arrive sequentially at the end of the row. The number of grooves N in a diffraction grating plays the role of the finesse F o a Fabry-Perot interferometer. From these figures, it is evident that the length of the line image is equal to the axial length of the lens, assuming that rays of light parallel to the optical axis enter along the entire extent of the lens. Consequently, the power P = 1>f of the doublet is P = P1 + P2 - 1P1P2 (36) For a cemented doublet of thin lenses, the powers are simply additive: P = P1 + P2 (37) For the case of the cemented doublet, incorporating Eqs. In general, the geometry of the mirrors and their separation determine the mode structure of the electromagnetic field in the laser cavity. The aperture in position (1) produces more barrel distortion than it does in position (2). The Jones vector of Eq. (9) represents an electric field vector whose tip travels in a counterclockwise direction as it traces out an ellipse whose symmetry axes are inclined at a general angle relative to the x,y-coordinate system. Recalling that the irradiance IW>m2 is proportional to the square of the amplitude of the electric field, we can say that the resultant irradiance of N identical but randomly phased sources is the sum of the individual irradiances. The hologram is a complex interference pattern of microscopically spaced fringes, not an image of the scene. 4 Two waves traveling together along the same line are given by y1 = 5 sin c vt + d 2 y2 = 7 sin c vt + p d 3 Write the form of the resultant wave. One technique for testing an optical system is to use a series of test patterns with sinusoidally varying darkness, each of a different spatial frequency. Indeed, the means by which the beam is originally narrowed is not relevant to the nature of the diffraction pattern that occurs, and E. 90 3 PHASE CHANGES ON REFLECTION The complex values of the reflection coefficient in Figures 3 and 5 indicate that for n - f f ff in certain situations, (19) and (22), we are able to characterize the beam parameters for beam propagation in any homogeneous medium of refractive index n. (b) When sufficient voltage is applied to the cell, the liquid-crystal molecules (except for those adjacent to the scratched glass plates) align with their long axis along the field direction. This can occur readily for low orders and therefore for thin films. In other, more complex, systems, the relevant quantities may be described as follows, 8, 9, 19. The two words here are amplification and stimulated emission. (30) E3 K32 E2 spb k31 sl when E21 hvp E1 k30 k10 k20 E0 Figure 5 Level structure of a four-level gain medium. On the other hand, a direct vision prism, Figure 16b, accomplishes zero deviation for a particular wavelength while at the same time providing dispersion. Example 2 Consider a situation in which an incident fundamental field of wavelength l0 = 0.8 mm is incident on a KDP crystal with refractive indices 1.4802 for the second harmonic and 1.5019 for the fundamental. For reflection from air to glass, as in the example just given, only 15% of the Es component is found in the reflected beam. (9) and (10), the regime of Fresnel, or near-field, diffraction may be expressed by 1 1 1 a + b b2 7 q 2 o near field. (11) Of course, this condition also applies to the other dimension (transverse to b) of the aperture, not shown in Figure 2. When a sheet of clear, polyvinyl alcohol is heated and stretched along a given direction, its long, hydrocarbon molecules tend to align in the direction of stretching. The line image is real, 18.75 cm past the lens and 15.75 cm long. Appendix 3-B. The Pockels cell can be used with the field oriented orthogonally to the beam direction, an arrangement that simplifies placement of the electrodes. That is, for constructive interference of light of free-space wavelength l0 (in vacuum) 2t cos ut = m l0 n (m = 0, 1, 2, A) (22) Both Es. The distance between the hanging mirrors can vary in response to passing gravitational waves. (10) and (11) allows the rate equations governing the population densities in the states 2 and 1 to be written as dN2 = -A 21N2 - B21g1n2 (21)>c2N2 + B12g1n2 (21)>c2N1 dt (20) dN1 = + A 21N2 + B21g1n2 (21)>c2N2 - B12g1n2 (21)>c2N1 dt (21) and (3) Following a particular convention, we choose to define the stimulated emission cross section s as s = B21g1n2hn>c Here we have assumed, for simplicity, that there is no degeneracy of the upper and lower states such as in s, is also the stimulated absorption cross section3 since, in this case, B12 = B21 . k, = 2p (14) Alternatively, if the wave is viewed from a fixed position, as in Figure 2b, it is periodic in time with a repetitive temporal unit called the period T. Solution The small-signal gain coefficient must exceed the threshold gain coefficient for lasing action to occur. The curves of Figure 4 have been calculated using the theory presented in this chapter. Repeat (b) when the angle of incidence from air (relative to the normal) is 30°. In particular, let E0x = A and E0y = B, where A and B are positive numbers. In that 569 570 Chapter 26 Laser Operation where the photon number density is related to ... = ln(¢N>¢N) Using this fact we can write the threshold population difference is ... (4) The cavity is constructed from two mirrors. 15 Light is ... 2 The rate equation for the photon number density can be formed by adding the contribution originating from cavity losses to the contribution originating from the interaction with the gain medium. What is the radius of the last zone in the drawing? This image is called the exit pupil of the optical system. Example 1 Consider 4-mW, TEM00 helium-neon (He-Ne) laser 1l = 632.8 nm2 with cavity length d = 1 m shown in Figure 7. Coherence of Light. Thus, Re 1n2 = nR must have the same sign as the orb' any refractive index, and 1n2 = nI , called the extinction coefficient, determines the rate of absorption of the wave in the conductive medium. A schematic eye (after H. An examination of Eq. (10), for z = 0, indicates that the imaginary part of q(0) must be negative so that the field amplitude does not grow without bound as x and y tend to infinity. 110 Chapter 4 Wave Equations along the y-direction is always p>2 out of phase with the x-component of the electric field, leading to circular polarization. The resultant vibration takes place along a line with negative slope. Such a pulsed-pump or gain-switched system can produce usable pulses as suggested by Figure 13. TM up or r Figure 6 Brewster window. A common atomic- level structure that serves as a gain medium is illustrated in Figure 5. Since the real and imaginary parts of the numerator and denominator are the same, except for sign, the magnitudes of the numerator and denominator are equal, and rTE has unit amplitude. Pedrotti and L. Notice that to maximize the mode number m, Eq. (35) requires that the plate separation d be as large as possible. What is the irradiance of the first three orders of interference fringes, relative to the zeroth-order maximum? Notice that this general form does indeed reduce to the Jones vectors found for a 2 x 2 a x 3 3 (a) y 3 3 1 3 1 2 1 2 (b) Figure 3 (a) Linearly polarized electric field vectors whose x- and y-components are in phase lie in the first and third quadrants. Thus, each successful mode of propagation in the waveguide has an integer mode number m, related to a direction um and given by m 2n1d cos um l (8) For our present purposes, the precise number of allowable modes is not as important as the qualitative dependence of the mode order m on the fiber characteristics. For a given mode, the angle between the ray and the fiber axis varies with l. Robinson, Glen M., David M. If the electric field amplitude of the wave is known to be 100 V/m, find 3RT A M B + Ey sin1kz - vt + w0y2x Produce plots like those in Figure 12 that show the evolution of the electric field over time, as a function of time over one complete temporal cycle for the following cases. Fresnel offered satisfactory methods for simplifying this task, or avoiding it altogether. Find the equivalent focal length of the combination and the position of the foci and principal planes using the matrix approach. If the laser is not excited, it repels the F atom and so the lower lasing level is unstable with an extremely short lifetime 1 10-13 s2. The near point (closest point of accommodation) moves further away from the eye with advancing age, starting at a position of 7 to 10 cm from the eye for a teenager, increasing to 20 to 40 cm for a middleaged adult, and extending to as far as 200 cm in later years. Why then does the spectrum also show a central spot, the DC component with m = 0? Adopting a wave theory, Huygens was able to derive the laws of reflection and refraction and to explain double refraction in calcite as well. Consider the interference term, I12 = 2e0c8E1 # E29 B B (6) B where E1 and E2 are given by Eqs. Residual impurities, such as the transitional metal ions (Fe, Cu, Co, Ni, Mn, Cr, V) and, in particular, the hydroxyl (OH) ion, also contribute to absorption, the last producing significant losses in the near IR region of 1.4 mm. (d) Lens N x Microdefect Lens (b) Figure 5 Radiation loss from an optical fiber because of (a) a sharp bend and (b) microdefects at the fiber surface. 25 The total delay time dt due to both modal distortion and material dispersion is given by 1dt22 = 1dtmod22 + 1dtmat22 Determine the total delay time in a 1-km fiber for which n1 = 1.46, e = 1%, l = 820 nm, and ¢l = 40 nm. B 19 Geometrical Optics of Fresnel diffraction. The bisectors of angles in Figure 21b Principal Problem 8. Consider a ray traced through two (x, y) planes the lines OA and OB form the sharp edges of the shadow to the right of the aperture. Only one has been listed here for use in a Pockels cell. Callen, and W. The holes S1 , and S2 of Figure 3 are usually replaced by parallel, narrow slits (oriented with their long sides perpendicular to the page in Figure 3) to illuminate more fully the interference pattern. Thus, fringe separation is proportional both to wavelength and screen distance and inversely proportional to the hole spacing. What is the angle of incidence? 5.7 cm 16. From your results in parts (a) and (b), calculate the resolving power in second order. As the following example indicates, for macroscopic light sources, the energy of a photon is typically far less than the total detected energy, and so, in such a case, the restriction that the detected energy must be only a multiple of a photon's energy goes unnoticed. Whereas the eye provides a qualitative and subjective response, the detectors discussed in this chapter provide a quantitative and objective response. The nearest aperture clearly cannot be greater than unity, unless f0 7 1. Extend the "table" to include the case m = 2, n = 0. The cleaved edges of these p-n junctions, of submillimeter dimensions, act as mirrors, providing feedback for the laser system. This leaves N E20 = a E20 i = NE20 (17) i=1 because there are N sources of equal amplitude. PROBLEMS 1 An object measures 2 cm high above the axis of an optical system consisting of a 2-cm aperture stop and a thin convex lens of 5-cm focal length and 5-cm aperture. Correcting for both defects is accomplished with sphero-cylindrical lenses, spherical surfaces to correct for myopia and cylindrical surfaces to correct for astigmatism. Under these conditions, Eq. (22) gives 1r2min = 33.6 * 10-5 rad, for an average wavelength of 550 nm. Image Brightness. Aperture Stops and Pupils Aperture Stop (AS) The aperture stop of an optical system is the actual physical component that limits the size of the maximum cone of rays—from an axial object point to a conjugate image point—that can be processed by the entire system. 609 Gouws, J.-P. and I. Determine the vergence of an object point 12 cm from the unit and the total of the tubing. Consider the corresponding configuration. In this arrangement, oblique chief rays, now determined by the aperture, do not penetrate the lens center. Let us examine the key biological components of the eye and their respective functions. (b) Determine the numerical aperture of the fiber. Thus, the irradiance is proportional to the square of the amplitude of the electric field. Hence, we find that the pronounced advantage of the interference grating is the absence of ghosts and the lowered background of scattered light. Generalizing this process of recording the phase and amplitude of a wave, in which only the irradiance is recorded. Relativistic Effects in Lasers. In addition to freedom from the expense and laboriousness of precise ruling of grooves over a large area, the interference grating also exhibits a... Whenever light is transmitted into a more dense medium, Light Wave and Optical Media. It is very quantitative is the number of intermediate subsidiary maxima. ... the lens and it illuminates fully the entire large spot, with the peak and the sharp edge is also a gravitational wave detector... Some Maxwell equations in each complex number... Fraunhofer diffraction. Adding all the contributions... In this case, the fourier Maxwell equations for a dielectric can be written B B $# E = 0 (18) B B $ * E = - 0B 0t (19) B B $ # B = 0 (20) B B $ * B = e0 m0 0E 0t (21) 540 Chapter 25 Optical Properties of Materials Now we take the curl of both sides of Eq. (19), giving B 0B B $ * ($ * E) ... There are thus three light waves of different frequencies... (a) plane waves, (b) spherical waves... we can write the intensity of each of the two beams... Thus no modulation of the beam occurs. Furthermore, one must keep in mind that this treatment assumes a uniform irradiance... The spreading described by Eq. (15) has been discussed on the basis of Fraunhofer, or farfield, diffraction, which means here that L must remain reasonably large. p = s¿ - s¿ + s is given byl 1 1 n1 + 2 c s + 41n + 12ps = - e¿ = 3 n1n - 12 n - 1 sh sp 8f + 13n + 22 1n - 12p2 + n3 d n - 1 (28) One can show further (problem 11), that minimum (but not zero!) spherical aberration results when the bending is such that s = - 21n2 - 12 p n + 2 (29) Notice that for an object at infinity s 0.7 for a lens of refractive index n = 1.50. Unlike an ordinary mirror, the PCM is able to respond immediately to varying spatial and temporal features of an incident wave such that a phase conjugate wave is continuously produced. The resulting phasor, shown in Figure 14a, has both an x-component and a y-component. Find the irradiance at point P as well as the irradiance at screen-observation points a vertical displacement y above or below the point P. Determine its resolution when used in a Littrow mount. In the series of calculations leading to the four radii of curvature, a calculation that is easily programmed, Eqs. Q-switching simply redistributes the energy so that it comes out in large bursts separated by periods of nearly zero energy output. What fraction of the total light is lost due to the hole in the mirror? (b) Explain why the two surface images of the whole surface are considered positive and to the left, respectively. When the surfaces are illuminated by a plane wave from the left, the optical path difference between... and green lines of mercury at 435.8 nm and 546.1 nm, respectively. Increasing the thickness t by 1>2, for example, changes the order of any fringe by m = 1, that is, the fringe pattern translates by one whole fringe. The transmitted field ET can be found by propagating the right-going cavity field E1 at Mirror 1 through the cavity and out of Mirror 2, ET1 = t2E2 = E0tte¿i1 + r2e2 e = tt'E1 ... (36) a Figure 3 Optical Interferometry Interference is proportional to the square of the magnitude of the field amplitude, IT r E0tE, so the transmittance of the Fabry-Perot cavity is T K IT>I0 ... Therefore the two waves... (22) in the preceding expression and perform some simplification leads to E0T = t2e-id>2 1 ... (4) Consider now the coordinate... a Figure 12 Frequently used values of aberrations. We can now calculate the amplitudes of the two Fresnel zones... Then the position of an object would not change the diffraction pattern... 1 (12) If the wave is to be described at some specified instant... In both C and B the image is located... 1 Of K two... whose sum is the resultant E... Thus, the light spot... Lens... Rayleigh... The Gaussian-beam modes of a spherical mirror optical cavity have wavefront radii... Find the image formed by the lens... Ex D cos vt... Zero-order ... For example... within two wave... The most widely used fibers ... Some small values of the focal length... ... Since Er and Et... 21 Sketch the shape of a nonsymmetrical pulse before and after reflection from an ordinary mirror and before and after reflection from a PCM. So see objects closely and far away, the eye accommodates. Within two years of the centenary of the publication of Newton's Opticks, the Englishman Thomas Young performed a decisive experiment that seemed to demand a wave interpretation, turning the tide of support to the wave theory of light. Also shown is an oblique pencil of rays originating at the off-axis point Q. The hologram itself is a series of circular interference fringes that do not resemble the object, but the object may be reconstructed, as in Figure 1b, by placing the hologram back into the reference beam without the presence of the object O. Such a wave train is shown in Figure 8b, with regular discontinuities in phase, separated by the time interval t0. Thus, to calculate the diffraction pattern of the double slit at some point, one considers every point of the wavefront emerging from each slit as a source of wavelets whose superposition produces the resultant field. A crumpled piece of cellophane introduced between crossed polarizers shows a striking variety of colors, enhanced by the fact that light must pass through two or more thicknesses in certain regions, so that ¢w varies from point to point due to a (a) Figure 21 Photoelastic stress pattern for a beam resting on two supports and (b) lightly loaded at the center. (b) Modulation transfer function (MTF) for three optical systems plotted against spatial frequency. (b) Plot of the Fourier series of the resulting wave. The change in state of the visual pigment in the rods or cones is transformed into an electrical signal at the synapses that connect to the nerve impulse. These special cases are worth reviewing. Since each component travels with a speed determined by the corresponding refractive index, n T and n , the speeds are unequal. Generalizing, the matrix equation representing any number N of translations, reflections, and refractions is given by y y D = M D NNMN - 1 A M2M1 a a 0 (9) 147 Chapter 5 Matrix Methods in Paraxial Optics B1 M2 a1 a1 a0 y0 y2 y2 1 sl a m 3 a2 a1 a0 y0 y0 Figure 8 Lens. Only the small number of modes that experience a net round-trip gain will have gain to survive, as is depicted in Figure 10a. In our experimental setup, when the source S is a laser, the lenses are arranged, a laser, such a narrow slit causes appreciable spreading of the beam on the screen. At various angles, the standing wave will appear as sine waves of various amplitudes, like those shown in Figure 5b. Since typically vg g, the crossover occurs at v vg , dividing the frequency range into regions of high transmittance (and the opaque (and highly reflecting) regions. 1 To get in easily determine the autocorrelation integral of Eq. (30). 1 (a) In dTV: sin1- a¿2 = 0¿ s¿ s¿ = - 0¿, sin a¿ (40) The relevant equations describing the first refraction are included in Table 3 under the first column for the general case. Which quality as traveling waves? In a CRT display beams of electrons ("cathode rays") emitted from an electron gun into a vacuum tube are steered by electric or magnetic fields and strike a phosphorescent surface that emits light from the point at which the electrons strike the surface. 3 Show that Eqs. As a result, the images of vertical and horizontal details in the object scene are formed at the same distance from the cornea, and astigmatic blurring does not occur. Example Consider a £ e = 5 milliwatt Helium-Neon laser emitting a "pencil-like" beam with a divergence angle a of 1.3 milliradians. Since at this point the optical-path difference between the two interfering beams vanishes, one might expect a bright fringe. The phase difference at points C and D between emerging beams is due to the optical path difference between two paths ADB and ABC. 15 Superposition of Waves E 2 Reference plane for beam 2 Reference plane for beam 1 s2 Wavefronts E1 P s1 Figure 1 Superposition of two plane waves at point P, led to widespread applications in research and industry. Consider the following example. Thus this system approximates an ideal four-level laser system. Freeman. 9 10 Chapter 1 Nature of Light Example 2 A certain sensitive radar receiver detects an electromagnetic signal of frequency 100 MHz and power (energy/time) of 6.63 * 10-16 J>s. Clearly, Eq. (43) can be used if one knows a value for q1 somewhere in the cavity—say, at the left mirror—and the ABCD matrix for the optical system that must, consequently, extend from the left mirror through the right mirror-lens combination and on to the transverse plane containing the external beam waist. 189 Interference of Light PROBLEMS p b 2 a Figure 3 Superposition of two waves. Suppose that we may represent the quantity appearing in parentheses using the first two terms of the binomial expansion, 11 - x21>2 = 1 - x>2 + A . This concentration of light at an axial point shows that the zone plate operates as a lens with P as a focal point. The resolving power of a prism spectrograph thus represents an important performance parameter, which we shall evaluate in this section. 2ÉEO Carrier waves move with phase velocity yp. In Example 3 we show that in thermal equilibrium the excited-state population is less than that of the ground state. Galenhall, Fl.: Triad Scientific Publishers, 1974. Then from Table 1, and the fact that C1v and S1v) are odd functions we have C1- 22 = -0.7154 and S1-1.22 = -0.6234 Now the tip of the phasor corresponding to the field maximum is in the positive spiral at point E, which has coordinates C1 q 2 = S1 q 2 = 0.5. The irradiance at such a point on the screen corresponding to this first irradiance maximum is then given by Eq. (33) as I1 max = 105[0.5 - (-0.7154)]2 + [0.5 - (-0.6234)]2 (2 (0.5+0.6234)2)>2 = 2.7400 = 1.37Iu The irradiance at the first maximum is 1.37 times greater than the irradiance Iu for an unobstructed wavefront. A very useful minitheorem is that the product of a complex number with its complex conjugate equals the square of its absolute value. Combining Eqs. Equation (42) then takes the form 1n - ... for 4 p / ... k (3) In the static, or DC, case specified by v = 0, J = a Ne2 B bE mg (48) The static conductivity s, defined by Ohm's law, B B J = sE (45) Neg2 mg (46) then takes the theoretical form s = Since conductivities are usually measured, we rewrite Eq. (43) in terms of s, giving J = a B s B bE 1 - iv>g (47) 4 PROPAGATION OF LIGHT WAVES IN A METAL An electromagnetic wave propagating in the conducting medium satisfies Maxwell's equations (12) through (15). If we always use light rays directed from left to right, we can simply say, "by all imaging elements to its left." 53 54 Chapter 3 Optical Instrumentation A2 L1 L2 A2, A5 L2 a D Chief ray b a Chief ray 0 l a b a b EnP ExP Figure 2 Limitation of light rays in an optical system consisting of two positive lenses and an aperture A. Means of modifying the dispersion curve include the use of multiple cladding layers, control of the core/cladding index difference, and variation of the profile parameter as in GRIN fibers. Assume that when a signal containing these two wavelength components enters the interferometer through Input 1, the l2 light component exits the interferometer through Output 2 and the l1 light component exits the interferometer through Output 1. Calculate the wavelength of the light. Thus, for the case at hand, there are N - 1 = 7 zeroes, and as a consequence N - 2 = 6 secondary maxima, between the principal maxima. Chromatic Resolving Power If the wavelength difference between two components of the light incident on a prism is allowed to decrease, the ability of the prism to resolve them will ultimately fail. To see this effect, refer to Figure 11a. Then for a given difference of the interferometer, the product md is fixed, that is, ml = ml2¿. Dashed lines represent comparable fringes from a Michelson interferometer. Or, as in Figure 17c, for a convex mirror, the ray leaves point P heading toward focal point F behind the mirror, strikes the mirror, and reflects as a parallel ray. In the problem at hand, then, Fermat's principle requires that nodo + nidi = noso + nisi = constant (6) where the distances are defined in Figure 12. The electric field at P (as in Figure 1) due to diffraction through a circular aperture can then be written as x dA Ep = A Area P Figure 6 Geometry used in the integration over a circular aperture. Clearly, the image in a region of the image is very small, of the order of a degree. Since the rim of A (as is shown in the figure, we conclude that its conjugate aperture A is the aperture stop (AS) of the system. Figure 10 shows a Czerny-Turner system in a grating spectrometer. The effect of the rotator element is to transmit linearly polarized light whose direction of vibration has been, in this case, rotated counterclockwise by an angle b. Cambridge: Harvard University Press, 1970. Equation (14), considered in steady state 1dN2>dt = 02, gives The gain curve has a line shape A and B and the ... P and F and C dark lines are due to absorption by ... the Laplace equation... the Lorentz... ... dispersion in the gain medium... Laser Deviation Small dispersion Large dispersion Figure 13 Extreme cases showing the dispersion ... Three wavelengths and the deviation d for the two wavelengths... In Figure 1, they are equivalent to sr sin u = kr sin u = Since both waves are in harmonic motion... Such a tapered optical fiber... For this example... From these illustrations, there are ... As the ... in the hologram, ... the two beams... In the steady state, the... Figure 14... A much more general... as the ... 1. ... and the quantum... 4-mm radius... 13 Thin Film... ... where the ... Of course, the point ... A rather ...

near 550 nm. Briefly, homogeneous broadening mechanisms are those physical influences that broaden the linewidth of the frequency response of each atom in the medium in the same manner, whereas inhomogeneous broadening mechanisms affect different groups of atoms in different ways—typically making the central frequency of the lineshape function different for different atoms. The terms radiant energy, Qe1J = joules2, radiant energy density, we1J>m32, and radiant flux or radiant power, £ e1W = watts = J>s2, need no further explanation. These surfaces of constant phase are often called the wavefronts of the disturbance. When this is not the case and the curvature of the wavefront must be taken into account, we speak of Fresnel, or near-field, diffraction. Dye lasers have very large small-signal gain coefficients (4/cm or more) and very large gain bandwidths (50-100 nm). The quantity 1ytet)-ye)2 is just a complicated way of expressing the relative refractive index n, which we can show as follows: y(z) mi ytet = = n 2 yei y1 yt nt (45) In arriving at this result we have used mi = mt = m0 for nonmagnetic materials and the relation y2 = 1 me for the velocity of a plane electromagnetic wave. The answer, of course, depends on whether the light from S, traveling along the two distinct paths SAP1 and SBP1 , is temporally as well as spatially coherent. If the object plane is uniformly bright and the aperture is a circular hole, then a circle of radius O¿T¿ is uniformly illuminated in the image plane. The difference between the Doppler effect in sound and light waves is more than the difference in wave speeds. Consequently, these rays arrive at different times, broadening the square wave, as shown. In summary, electromagnetic waves are produced by oscillating (in general, simply accelerating) charges that carry energy (and momentum) as they travel. We denote the energy of this lower level by E1 with the nonzero thermal occupations in energy E2 - E1 = hn0 and take, again for the moment, the lower energy state to be the ground state of the system, shown in Figure 1. According to the Huygens-Fresnel principle, we can consider spherical wavelets to be emanating from each point of the wavefront as it reaches the plane of the slit and then calculate the resultant field at P by adding the waves according to the principle of superposition. Such scattering is most effective when the scattering centers are particles whose dimensions are small compared with the wavelength of the radiation, in which case we speak of Rayleigh scattering. The light beam striking the film is allowed to cover the edge of the film F, so that two fringe systems are seen side by side, corresponding to air films that differ by [illegible]. Images formed in mirrors do not suffer from chromatic aberration since the focal length of a mirror is independent of wavelength. Zubairy. 17 A filtered mercury lamp produces green light at 546.1 nm with a linewidth of 0.05 nm. Coupling a certain fraction of the laser light out of the cavity through the output coupler mirror to form the external laser beam. Further take the field in the cavity to be resonant with the cavity so that d = 2mp. Historically, dispersion has been characterized by using three wavelengths of light near the middle and ends of the visible spectrum. The fundamental lower limit of the noise inherent in the detection process is set by quantum or shot noise, but in practice the other technical noise sources often determine the noise equivalent power for the detector. Using the system matrix representing the hemisphere, determine the exit elevation and angle of a ray that enters parallel to the optical axis at an elevation of 1 cm. Write an equation describing the displacement y(x,t) of the traveling pulse as a function of time t and position x if it moves with a speed of 2.5 m/s in the negative x-direction. An Introduction to the Theory of Diffraction. The optical path difference ¢, in the case of normal incidence, is the additional path length ABC traveled by the refracted ray times the refractive index of the film. (31) After neglecting the smaller third term on the left side of this relation, comparison with Eq. (30) leads to the conclusion that R(z) does indeed play the role of the radius of curvature of the phase fronts of a Gaussian beam. Employing the Pythagorean theorem and the distances defined in Figure 6, we have AO = 2a2 + x2 and OB = 2b2 + 1c - x22 , so that t = 2a2 + x2 y + 2b2 + 1c - x22 [illegible] Construction to prove the law of refraction from Fermat's principle. (a) p = -2, q = +2, f1 = -6, f2 = +6, r = 4, s = -4 in. y = ae-b(x+10t) Chapter 6 2 4m (a) y = (x+(2.5 m/st) 2 +2 m2 3 (a) (1) and (2) qualify because they satisfy the wave equation; more simply, if w = z + vt, they are functions of w: y = A sin2 (4w) and y = Aw2 . Relative to the original object, the final image is 2>5 as large and inverted. SainteFoy, Quebec: Les Editions Le Griffon D'Argile, 1988. [illegible] It is important to note that c need not represent only physical displacements but could represent any quantity that varies in space and time such as the difference of air pressure from its equilibrium value (as in a sound wave) or the strength of an electric or magnetic field (as in a light wave). The Fabry-Perot cavities effectively extend the length of the arms by causing the light from the laser to sample the cavity length many times before exiting to the detector. [illegible] As soon as the medium of propagation is removed, there is no longer a physical basis for the distinction between moving observer and moving source. 143 Properties of Lasers 120 Relative spectral emission 100 80 60 40 20 0 895 899 903 905 907 911 915 Figure 10 Spectral output from a GaAs lightemitting diode. [illegible] After transmission by the optic fiber, it is recovered from an optical to an electrical signal. Figure 8 Correspondence between ordinary spherical waves and Gaussian spherical waves. If the glass has a refractive index of 1.50, determine (a) the required Coddington factor and (b) the radii of curvature of the lens. [illegible] Reflectance factor curves are shown in Figure 7. Introduction to Fourier Optics. [illegible] In Example 6 we show how one can estimate the signal power associated with a given gravitational strain. [illegible] We concluded that in order to transfer information at a high rate over long distances, a combination of source wavelength and single-mode fiber that minimizes attenuation and distortion should be used. The net angle of rotation b due to a light path L through a solution of d grams of active solute per cubic centimeter is, then, (4) b = rLd where L is in decimeters and d is the concentration in grams per cubic centimeter. 4 FRESNEL DIFFRACTION FROM CIRCULAR APERTURES Suppose the aperture in Figure 1 is circular. In general, the output of a laser will consist of those frequencies given in Eq. (26) that the laser gain medium is capable of supporting. We will develop first an expression for the CW output irradiance for a ring laser and then write down the corresponding result for the more common case of a laser system that uses a two-mirror linear cavity. All approach a MTF of 1 as the spatial frequency approaches zero but indicate different resolution limits as MTF becomes zero. Rays from an axial point O are limited in angle by the aperture and focused by the lens at point O¿. Determine the reflectance and transmittance for the TE mode at normal incidence and at 45°. The determination of the oscillator strength fj or even a quantum transition requires the application of quantum theory. We begin our treatment with a brief description of Fourier analysis, which we will need in this chapter. Calculate the number of photons arriving at the detector in one observation time in an optical signal of wavelength 1.3 mm with a power equal to the noise equivalent power of the detector. [illegible]

object and image are the same. If one looks into the optical system from the image, another image of the AS can be seen that appears to limit the output beam size. Field lens RO Reticle Retaining ring EL Field stop Exit pupil FL Figure 26 Ramsden eyepiece. In Figure 4, reflectance is plotted as a function of the angle of incidence u. When input light is modulated to convey information, the signal waveform becomes distorted due to several mechanisms to be discussed. Oscillations within the plane—where the electrons tend to be confined due to the chemical bonding—take place more OA OA y y儲 Ca y E儲 y儲 ¬ y 102 E O C Figure 9 (a) Progress of light through a calcite crystal. For situations in which the assumptions of Fraunhofer diffraction fail, we are left with Eq. (7). It turns out, in fact, that the phase of the electromagnetic wave originating with the oscillating electrons is 180° out of step with that of the incident radiation, so no wave can propagate in the forward direction. OA Extraordinary ray Ordinary ray OA 4 For a more complete discussion, see, for example, J-P Goure and I. For simplicity, light is shown transmitted or reflected from a single groove, even though diffraction involves the cooperative contribution from many grooves. That is, if the z-axis is the line of symmetry, then r = 2x2 + y2 . That is, show that A21 is the inverse of the lifetime of the atomic level. B The requirement for a rotator of angle b is that an E-vector, oscillating linearly at angle u and with normalized components cos u and sin u, be converted to one that oscillates linearly at angle 1u + b2. Solution Then, lS = yS 3 * 103 = = 1.5 * 10-5 m nS 2 * 103 Using Eq. (16), sin u = l 550 * 10-9 = = 0.0183 2lS 12211.5 * 10-52 so that u = 1.05° The acousto-optic (AO) effect can be applied to the modulation of a light beam by controlling its amplitude (AM), its frequency (FM), or its direction. This technique—referred to as nondestructive testing—is often applied to determine maximum stress points on the subject as pressure is applied, as in the case of an automobile tire, for example. The lamp is available in a wide variety of filament configurations and of bulb and base shapes. The system matrix connecting the object and image planes consists of the product of three matrices, corresponding to (1) a translation Ṗ1 in air from object to the rod, (2) a refraction Ṙ at the spherical surface, and (3) a translation Ṗ2 in plastic to the image. To sharpen our understanding of the coherence of a wavefield radiating from a source, consider the situation depicted in Figure 11. The length of the etalon can be chosen so that only a single etalon mode overlaps an existing cavity mode within the frequency range (the gain bandwidth) of laser operation. The situation described by Eq. (32) and 287 Fraunhofer Diffraction N 2 64 a: b: sin u: p 2p l a 2l a 3p p 3l a (a) N 2 I0 Figure 15 (a) Interference factor sin21Na2> sin21a2 (solid line) and diffraction factor sin2 b> b 2 (dashed line) plotted for multiple-slit Fraunhofer diffraction when N = 8 and a = 3b. 10 Let a collimated beam of white light fall on one refracting face of a prism and let the light emerging from the second face be focused by a lens onto a screen. An example involving the He-Ne laser is instructive. St. Louis: C. (a) Ideal, collimated beam is focused to a fictitious "point" in accordance with geometrical optics. From symmetry, it is clear that identical results would be obtained for the ys-variation. Interference fringes of equal thickness are produced by the air wedge between lens and optical flat. Lens L2 forms the Fraunhofer pattern in the spectrum plane. 9 Derive the Stefan-Boltzmann law from the Planck blackbody spectral radiance formula. f1 /f2 = n/(n − 1) 31. The Michelson interferometer is of this type. TABLE 1 REFRACTIVE INDICES FOR SEVERAL MATERIALS MEASURED AT SODIUM WAVELENGTH OF 589.3 nm Isotropic (cubic) Uniaxial (trigonal, tetragonal, hexagonal) Biaxial (triclinic, monoclinic, orthorhombic) Sodium chloride Diamond Fluorite Positive n 7>n : Ice Quartz 1SiO22 Zircon 1ZrSiO42 Rutile 1TiO22 Negative n 72, it is a quarter-wave plate (QWP); if ¢w = p, we have a halfwave plate (HWP); and so on. The length of the crystal is 1 cm. In conjunction with the optical transport of computer information through optical fibers, information handling, storage, and retrieval can all be done using light. OA l 589.3 nm Unpolarized light Figure 24 45 OA Angle of deviation Problem 10. An average can be taken for unpolarized light. 3. The secondary maxima of the single-slit diffraction pattern do not quite fall at the midpoints between zeros, even though this condition is more nearly 1 sinc b I/I0 sinc 2 b b ⩾3p ⩾2p ⩾p p 2p 3p kb sin u 2 Figure 2 Sinc function (solid line) plotted as a function of b. Notice further that if the screen is moved closer to the lens, it intercepts a sharp image II¿ of the object OO¿. Then, s2œ = 122.521 - 152 s2f = = - 9 cm s2 - f 122.52 - 1-152 m2 = - s2œ -9 = = + 0.4 s2 22.5 Thus, the final image is virtual (because s2œ is negative), 9 cm to the left of the seconds lens, erect with respect to its own object (because m is positive), and 0.4 times its size. For example, if the Pockels cell is to behave as a half-wave plate, we need to make £ = p. How does this affect the holographic image under white-light viewing? In one configuration of the Pockels cell, the natural optic axis of the crystal is aligned parallel to the applied field. The extraordinary ray is so named because it does not exhibit ordinary Snell's law behavior on refraction at the crystal surfaces. Radiation from the small hole has an emissivity that is essentially constant and equal to unity. Consider a transition wavelength of l0 = 488 nm and take the temperature of the gas under the operating conditions to be 3000 K. Equations (9) and (10) now permit us to plot the variation of irradiance with vertical displacement y from the symmetry axis at the screen. 12 a. Example 4 A Huygens eyepiece uses two lenses having focal lengths of 6.25 cm and 2.50 cm, respectively. Is the noise equivalent power for this detector a result of the intrinsic quantum fluctuations in the incident laser field? When M¿ and the film surface are not precisely parallel, the usual Fizeau fringes due to a wedge will be seen through the microscope, which has been prefocused on the film. Their optic axes are parallel, 363 Production of Polarized Light 1.59 Principal indices of refraction 1.58 1.57 Slowest extraordinary ray n儲 1.56 1.55 Ordinary ray n忈 1.54 1.53 200 300 400 500 600 700 800 900 1000 Wavelength (nm) with the orientation perpendicular to the page as shown. What is the wavelength of the light? The actual interferometer in Figure 1a possesses two optical axes at right angles to one another. When light from the first point A, Figure 5, reaches the second point B after reflection from a plane surface, however, the same principle predicts the law of reflection, as follows. (Canrad-Hanovia, Inc.) Flash tubes represent a high output source of visible and near-infrared radiation, produced by a rapid discharge of stored electrical energy through a gas-filled tube. A thin layer of nickel is deposited onto the hologram and then is peeled off. The response of the electron to this driving force depends on the relationship between the driving frequency v and the natural or resonant frequency of the oscillator v0 . By Fermat's principle, these are isochronous rays. Broader regions of low reflectance also become possible in the visible region of the spectrum, once the restriction of using equal l>4 coatings is relaxed. Example 1 The shortest wavelength of light present in a given source is 400 nm. Show that if the maximum positive displacement of a sinusoidal wave occurs at distance x0 cm from the origin when t = 0, its initial phase angle w0 is given by w0 = p 2p - a b x0 2 l (a) the amplitude of the magnetic field and (b) the average magnitude of the Poynting vector. Restrictions on possible modes will be described later. 1 ONE-DIMENSIONAL WAVE EQUATION The most general form of a one-dimensional traveling wave, and the differential equation it satisfies, can be determined in the following way. Many ordinary materials also show birefringence, either under normal conditions or under stress, as in Figure 21. That is, the spontaneous emission from a sample of atoms all in the same excited state will occur with a range of frequencies characterized by the linewidth ¢n. Here, n1 is the index of refraction of the medium containing the incident beam. Virtual objects occur only with a sequence of two or more reflecting or refracting elements and are considered later. Another useful form of Eq. (14), for the case of interfering beams of equal amplitude so that I1 = I2 = I0 , is found by writing I = I0 + I0 + 2 2I20 cos d = 2I011 + cos d2 and then making use of the trigonometric identity d 1 + cos d K 2 cos2 a b 2 The irradiance for two equal interfering beams is then d I = 4I0 cos2 a b 2 (18) Notice that energy is not conserved at each point of the superposition, that is, I Z 2I0 , but that over at least one spatial period of the fringe pattern Iav = 2I0 . Details are to be worked out in a series of problems at the end of this chapter. In addition, the quadrupole nature of the gravitational waves leads to signals of unique signature. 14 A light beam passes consecutively through (1) a linear polarizer with TA at 45° clockwise from vertical, (2) a QWP with SA vertical, (3) a linear polarizer with TA horizontal, (4) a HWP with FA horizontal, (5) a linear polarizer with TA vertical. Consequently, violet light is deviated most in refraction through the prism. The energy E of the charge carriers varies across the band since the carriers in a given band vary in momentum, pc . Chapter 19 Feynman, Richard P., Robert B. Nevertheless, there will generally be several photons—let us call them "seed" photons—directed along the optical axis of the laser. According to Eq. (33), the square of the length of a straight line drawn between any two points of the spiral must be proportional to the irradiance at point P, since C1y2 and S1y2 are coordinates in a rectangular coordinate system. The angle a in Figure 22 may be specified in two ways, tan a D s0œ and tan a d x so that x ds0œ D (29) It is then required to find, from the lens equation, the object distance s1 corresponding to image distance s0œ + x and the object distance s2 corresponding to image distance s0œ - x. Example 2 A laser beam of radius 1 mm carries a power of 6 kW. E = E0 cos1kz - vt2xN + E0 cos a kz - vt + byN 2 3 Describe as completely as possible amplitude, wave direction, and the state of polarization of each of the following waves. It is typically the case that the electromagnetic boundary conditions at the mirror surfaces require that the electric field be zero at the mirrors, which then implies that standing wave nodes occur at the mirrors. The resultant phasor, which includes two full half-period zones, is A 2 . Figure 16 Representative sketches of irradiance or burn pattern for several different orders of Hermite-Gaussian optical resonator modes as they might be photographed in the output beam of a laser oscillator. There are various devices that accomplish this. ' A complex number z is expressed as the sum of its real and imaginary parts, ' z = a + ib |~ z| b u a (11) Re where ' a = Re1z 2 and ' b = Im1z 2 are real numbers and i = 2 - 1. What is the luminous flux incident on the small surface? For the average person, presbyopia (loss of accommodation) sets in during the early 40s, signaling the need for reading glasses to restore the near point to a comfortable position near 25 cm or so. If each film has an optical thickness of lf>4, a little analysis shows that in this case all emerging beams are in phase. If the lines of the Ronchi ruling have gradually changing opacity, such that the amplitude transmitted varies sinusoidally, we have the sinusoidal grating. Determine the modal distortion for this fiber. According to Huygens, every point of a given wavefront of light can be considered a source of secondary spherical wavelets. Large resolving powers are, of course, desirable. 20 a. 7 Nonlinear Optics and the Modulation of Light crystal therefore behaves as a phase retarder, and the component waves emerge with a phase difference. On the other hand, once refracted by the lens, the wavefronts contract, in Figure 25a, and expand further, in Figure 25b, to locate the real and virtual image points shown. Calculate the phase difference between TM and TE modes for internally reflected rays at angles of incidence of 0°, 20°, 40°, 50°, 70°, and 90°. Show that r1l2, which we define to be the energy per volume per unit wavelength interval in the field, is r1l2 = 8ph l5 a 1 ehc>lkBT - 1 b b. 1 THE FRESNEL EQUATIONS Consider Figure 1, which shows a ray of light incident at point P on a plane interface—the xy boundary plane—and the resulting reflected and refracted rays. Scaled transmittance Scaled transmittance 21 Consider a light source consisting of two components with different wavelength l1 and l2 . Refer to Figure 17a, b, and c in connection with the following description of how the three key rays can be drawn. The length HE, in Figure 14b is proportional to the irradiance of the first minimum on the screen. Equation (53) can be used to relate the output irradiance to the input irradiance of an inhomogeneously broadened gain cell using the same procedure that led to Eq. (41). 436 nm One mirror makes a wedge angle of 0.0172° with the image of the other, reflected through the beam splitter. In Figure 8, the basic law of propagation for each type of wave and the effect of a lens on reshaping the propagating wavefront is illustrated. Energy levels with such long lifetimes are often referred to as metastable states. 544 Chapter 25 Optical Properties of Materials 3 CONDUCTION CURRENT IN A METAL In metals, the existence of "free" electrons, not bound to particular nuclei, modifies the treatment outlined above for dielectrics. s f (a) These rules5 can be quickly summarized by noticing that positive object and image distances correspond to real objects and real images and that convex mirrors have positive radii of curvature. Note also that to maintain A¿DB as a single straight line, the reflected ray must remain within the plane of incidence, that is, the plane of the page. What is the ratio of the population densities of these two energy levels if the assembly of atoms is in thermal equilibrium as a temperature of T = 300 K? 4, 5, and Joseph W. For simplicity, only one refraction is shown. If the subject beam alone were present, the film would be darkened in proportion to the irradiance of the subject beam. Since the convergence of the rays striking the second surface is determined by the position of the first image, its location now specifies the appropriate object distance to be used for the second refraction. For an exit slit of 0.02 cm, what is the coherence time and coherence length of the light of mean wavelength 5000 Å? A zero path difference for these rays implies the condition of geometrical optics: For transmitted light, Figure 4, the diffraction peak is in the direction of the incident beam; for reflected light, Figure 5, it is in the direction of the specularly reflected beam. When yp = yg , the high-frequency waves and envelope would move together at the same rate, without relative motion. Consider the arrangement of Figure 8. In fact, these fields do interfere but the interference term averages to zero over the averaging times of most real detectors. Combining the last three equations, V 兩g兩 g1t2 = ƒ g ƒ eivt (32) Re g1t2 = ƒ g ƒ cos vt (33) t0 Recalling the empirical expression for visibility, Imax - Imin V = Imax + Imin 1 (34) t Figure 10 Fringe visibility or degree of coherence as a function of the difference in arrival times of two waves with coherence time t0 . Since the smallest ratio of nL>nH yields best reflectances, high-reflectance stacks may be fabricated from alternating layers of MgF2 1nL = 1.382 and ZnS 1nH = 2.352 or TiO2 1nH = 2.402. The numerator of the Snellen fraction expresses the fixed testing distance, and the 427 428 Chapter 19 Optics of the Eye 20 100 20 40 20 20 5 of arc Eye 1 of arc Test distance Figure 4 Construction of a Snellen eyechart letter H to measure visual acuity. For the present, we treat electric fields as scalar B quantities. All the light originating from a single point of the scene and collected by the lens is focused to a single conjugate point in the image. The squares of the coefficients in the Fourier series are proportional to the irradiances of the corresponding diffraction spots. In problem 4, use Eqs. However, the gain provided must exceed the losses encountered per round-trip due to imperfect mirrors, transmission from the output mirror, and other cavity loss mechanisms. Determine which element (A, L1 , or L2) serves as the aperture stop AS. In many cases of interest, other factors can lead to a phase difference between the beams as well. Spontaneous decay from either of these levels removes that atom from the coherent interaction with the field. 8 Stewart E. In responding to these oscillating fields, the charges themselves oscillate and act as radiators of secondary electromagnetic waves. Clearly, the required length of fiber and the cost of components play major roles in determining the selection of the best system for a specific application. Irregularities in the surface of the lens show up as distortions in the concentric ring pattern. Diffracted slit images are formed at the Rowland circle. Solid-State Lasers Solid-state lasers are a class of lasers in which the lasing atomic species is doped into a transparent host material. 41 Geometrical Optics The units of the terms in Eq. (32) are reciprocal lengths. 5 Using the result of problem 4, determine the wave aberration, transverse aberration, and longitudinal aberration for a spherical mirror of 2-m focal length and 50-cm diameter, when it forms an image of a distant point object. The sun subtends an angle of 0.5° at the earth's surface. The radii of curvature of the beam wavefronts must match the mirror radii of curvature. 23 Design an achromatic doublet of -10-cm focal length, using 573/574 and 689/312 glasses. Evaluation of the integrals in Eqs. Since there will be a spread of k values in the source, Ik can be interpreted as irradiance I(k) per unit k interval at k, giving an integrated irradiance over all wavelengths of q I = L0 I1k2 dk = 2I01k2 dk - q L0 2I01k2cos1kx2 dk q L0 (40) The first term in the result behaves as a bias term, representing the constant integrated irradiance due to all wavelength components in the two noninterfering beams added together. Destructive interference occurs at this wavelength and to some extent at neighboring wavelengths, which means that the light reflected from such a film is the incident spectrum minus the wavelength region around l0 . Finally, because the direction from various aperture points O to a given field point P may no longer be considered approximately constant, the dependence of amplitude on direction of the Huygens wavelets originating at the aperture must be considered. When the absorption of radiation by the focusing elements is severe, as in the vacuum ultraviolet (about 1 to 200 nm), the focusing and diffraction may both be accomplished by using a concave grating, that is, a concave mirror that has been ruled to form grooves onto its reflecting surface. Figure 15 Fiber-optic communications system using wavelength-division multiplexing. One usually views the virtual image by looking into the hologram. The shim is pressed onto a material like mylar by a roller under conditions of high pressure and temperature. The second number refers to the cylinder power, the power of the cylindrical surface superimposed on the back surface of the spectacle lens required to correct for astigmatism. For this purpose a second lens of flint glass 1n = 1.72002 is added. That the gain coefficient is less for fields of larger irradiance is said to be due to gain saturation. Therefore, e0c 1b 1E022 2 e0c = 1b 2E022 2 I1P = I2P Using these relations and Eq. (20) in Eq. (26) gives, g1t2 = 8E0e -ivteif1t2E0eiv1t + t2e -if1t + t29 e0c b1b2 2 21e0c>2221b 1 b 2E 022 234 Chapter 9 Coherence 2p Phase w(t) w(t t) t p 2t0 t0 3t0 4t0 t (a) Phase difference w(t) w(t t) p Figure 9 (a) Random phase fluctuations w1t2 every t0 of a wave (solid line) and the same phase fluctuations w1t + t2 of the wave (dashed line) at a time t earlier. The hologram is now a complex montage of zones in which is coded all the information of the wavefront from the scene. The following example will provide practice with the thin-lens formula 1>s + 1>s¿ = 1>f and procedures for determining stops and pupils for a specific optical system. 5 THE BEAT PHENOMENON Yet another case of superposition, with important applications in optics, is that of waves of the same or comparable amplitude but differing in frequency. 274 Chapter 11 Fraunhofer Diffraction Example 2 Imagine a parallel beam of 546-nm light of width b = 0.5 mm propagating a distance of 10 m across the laboratory. (28) Equation (28) is called the lensmaker's equation because it predicts the focal length of a lens fabricated with a given refractive index and radii of curvature and used in a medium of refractive index n1 . 4 THE FABRY-PEROT INTERFEROMETER The Fabry-Perot interferometer makes use of an arrangement similar to the plane parallel plate to produce an interference pattern that results from the superposition of the multiple beams of the transmitted light. In attempting to explain physical phenomena, it is natural that we appeal to well-known physical models like waves and particles. Wavefront W2 is an example of the actual wavefront, an aspherical envelope whose shape represents an exact solution of the optical system. How far must the ocular be moved from its normal position? When the net phase difference ¢w = p>2, the retardation plate is called a quarter-wave plate; when it is p, it is called a half-wave plate. From the matrix elements, determine the first and second focal points and the first and second principal points relative to the corneal surface. Thus for N randomly phased sources, the squares of the individual amplitudes add to produce the square of the resultant amplitude. Approximate the Cauchy constants A and B for crown and flint glasses, using data for the C and F Fraunhofer lines from Table 1. Roughly, if states with nominal energies En and Em have energy widths ¢En and ¢Em , respectively, a photon should have energy in the range hn = En - Em - 1¢En + ¢Em2 1¢En + ¢Em2 to hn = En - Em + 2 2 in order to significantly interact with the atom. 9 FABRY-PEROT FIGURES OF MERIT As we have seen, the Fabry-Perot interferometer is a flexible device that has many modes of operation. There are six cardinal points on the axis of a thick lens, from which its imaging properties can be deduced. With no voltage applied across a given pixel, half of the unpolarized ambient light first passes through the vertical polarizer at the input side of the cell, then the polarization of this light is rotated so that it passes the horizontal polarizer at the end of the cell, reflects from the mirror, and retraces its steps so that vertically polarized light emerges from the display panel. When the laser frequency strays from the resonant frequency of the Fabry-Perot interferometer, the resultant dip in the transmittance of the Fabry-Perot can be used to initiate a feedback signal used to return the laser frequency to the resonant frequency of the Fabry-Perot cavity. The polarization is not complete, both because we see light that is multiply scattered into the eye and because not all electronic oscillators in molecules B are free to oscillate in exactly the same direction as the incident E-vector of the light. The sinusoids corresponding to object O and image I are described by their contrast modulation g, given by g0 = 1/K C (36) where £ is illustrated in Figure 10a. How many independent modes can propagate in this waveguide if d = 5l and d = 50l? Feynman, Robert B. If, in the making of this hologram, the object point O is moved farther away, the radius of each zone increases. The beam-waist radius w0 is determined by the design of the laser cavity and depends on the radii of curvature of the two mirrors and the distance between the mirrors. We examine first the role of aperture stops and their related pupils in fixing image brightness, then the role of field stops and their related windows in determining a field of view. Since the output element described in problem 7 is essentially a thin lens, compare the ABCD matrix obtained in problem 7(b) with the thin-lens matrix, namely, 1 C- 1 f (Hint: Is the transverse plane, 50 m from the beam waist, far enough away to be in the far field? The indices nᵖ and nᶜ are much closer in value than n and n 7, as can be seen in the case of quartz (Table 3). This resolution criterion, ¢d Ú 2 ¢d1>2 K ¢dmin, is illustrated in Figure 13. Achieving zero reflectance at some wavelength may not satisfy the very common need to reduce reflectance over a broad region of the visible spectrum. In addition we used Eqs. With vp W vg , plots of the cosine functions versus time may appear like those of Figure 7a, calculated at the same point x0 . The spectral output of the light source is characterized both by a central wavelength l and a spectral width ¢l. Show that this result can be expressed as ¢u = 1l>yS2 ¢nS where l is the wavelength in the medium. Pumps can be optical, electrical, chemical, or thermal in nature, so long as they provide energy that can be coupled into the laser medium to excite the atoms and create the required population inversion. 33 Show that the angular magnification of a Newtonian reflecting telescope is given by the ratio of objective to ocular Lens Mirror am h ao Fo , Fe C ao fe fo Object Figure 40 Problem 33. In addition, through a variety of mechanisms, anisotropic losses can be introduced into the fiber so that one of the orthogonal polarization modes is highly attenuated while the other travels long distances with low loss. Determine their optimum separation in reducing chromatic aberration, their equivalent focal length, and their angular magnification when viewing an image at infinity. In what range of the electromagnetic spectrum are the spectral lines of the Balmer series? In the Michelson interferometer, fringes appear localized on the mirror and so cannot be seen in sharp focus at the same time as a test object placed in one of its arms. 16 17. The functions R(z) and w(z) can be determined by using Eq. (14) in Eq. (17) and performing some complex algebra. The parallel rays enter the lens from a distant object at altitudes of 1 and 5 mm above the optical axis. The free spectral range of the Fabry-Perot cavity used in the experiment was known to be 11.6 GHz. The free spectral range can be taken to be the distance between the tall transmittance peaks, indicated by the arrows in Figure 21b. Then, ' E eiwx A 1 E0 = c 0x iwy d = c ip>2 d = A c d E0ye Aei P E Recalling that v = 2pn = 2p>T, each of the cases in Figure 5 can be easily verified. The object distance of the nth step is determined by the image distance for the 1n - 12th step. Thus, E = mc2 + EK = 0.511 MeV + 2.5 MeV = 3.011 MeV or E = 3.011 * 106 eV * 11.602 * 10-19 J>eV2 = 4.82 * 10-13 J The other quantities are then calculated in order. Evidently, a1 = a0 y1 = y0 + L tan a0 and These equations may be put into an ordered form, y1 = 112y0 + 1L2a0 a1 = 102y0 + 112a0 (7) where the paraxial approximation tan a0 a0 has been used. By comparison with Eq. (13), the theory predicts a dependence of the empirical Verdet constant V given by V = e dn l 2mc dl (15) The magnetic field analogs of the Kerr effect (where ¢n r E 2) are the Voigt effect (in gases) and the Cotton-Mouton effect (in liquids), in which a constant magnetic field is applied normal to the light-beam direction. 5 ESSENTIAL ELEMENTS OF A LASER The laser device is an optical oscillator that emits an intense, highly collimated beam of coherent radiation. The two reflected rays diverge as they leave the mirror. The transmittance is a maximum whenever d = 2kd = 2 2p d = 2mp l m = 0, ; 1, ;2 Á Rearrangement gives the condition for a maximum as dm = ml>2 (35) Accordingly, the free spectral range in this mode of operation is dfsr = dm + 1 - dm = l>2 (36) The cavity length change required to move from one transmittance peak to another is thus a measure of the wavelength of the source. The resolving power of imaging fibers depends on the accuracy of fiber alignment and, as might be expected, on the individual fiber diameter d. Optical Detectors and Displays Silicon-based photodiodes are sensitive to optical radiation with wavelengths ranging from 190 to 1100 nm, and Indium-Gallium-Arsenide (InGaAs) p-n junction photodiodes can be used to detect radiation with wavelengths ranging from 800 to 1800 nm. This is Bessel's method for finding the focal length of a lens. The principal points and nodal points often move outside the optical system, that is, outside the region defined by the input and output planes. Inasmuch as the y-axis is an axis of symmetry, the corresponding bright fringe surfaces are generated by rotating the entire pattern about the y-axis. Kittel, Charles. Introduction to Solid State Physics. 3 A double convex lens has a diameter of 5 cm and zero thickness at its edges. These empty spaces are called holes and act as positive charge carriers. Many different transverse irradiance patterns, called TEM modes, can be present in the output laser beam. Night vision, which takes place with large, adapted pupils of around 8 mm, is capable of higher resolution than daylight vision. 8 a. Volume Holograms When the thickness of the film emulsion is large compared with the fringe spacing, the hologram may be considered a three-dimensional, or volume hologram. Chapter 3 1. Images such as these can be used to map the temperature variation across the surface of the earth, for example. The image S; cannot be projected on a screen as in the case of a real image. The object subtends the angle a at the unaided eye and the angle a_c at the eyepiece. Suppose an energy fraction a is transmitted in the first case and a fraction b is transmitted in the second. Determine the minimum number of grooves required. Focused images have the shape of the collimator slit (not shown). Positive charges are associated with 535 536 Chapter 25 Optical Properties of Materials the constituent nuclei and negative charges with the electrons bound to such nuclei. In both cases, the lens is large enough to intercept the entire cone of rays admitted by A. In practice, rays of light contributing to an image in an optical system are, in fact, usually rays in the near neighborhood of the optical axis. Note that Eq. (43) is only meaningful when the vacuum wavelength of light exceeds a certain threshold value, q_{th} = 1 In 1?1S2 L I Ring cavity2 (44) since it predicts a negative irradiance when q_0 6 q_{th} . Because such plates are extremely thin, it is more practical to make thicker QWPs of higher order m, giving dw = 12p2m + p>2, where m = 1, 2, 3. A . By using a lens separation slightly smaller than f, the reticle is in focus at a position slightly in front of the lens, as shown in the ray diagram of Figure 26-6 and in Figure 27. Sp 3p p 0 p 3p 0 Sp (b) Resulting fringes, shown in Figure 20b, now exhibit better contrast. The interferometer consists of two 50-50 beam splitters, BS1 and BS2, and two mirrors, M1 and M2. The correct form for the spectral existance Ml of a blackbody was first derived in 1900 by Max Planck, who found it necessary to postulate quantization in the process of radiation and absorption by the blackbody. Let the refractive index n of the emulsion be equal to 1. It should be emphasized that the forms given in Table 1 are not unique. Diffraction Gratings. In other words, the detector, together with its associated amplifier and circuits, should provide a linear response, with output proportional to input. Photons of a certain resonant energy must be created in the laser cavity, must interact with atoms, and must be amplified via stimulated emission, all while bouncing back and forth between the mirrors of the resonator. Suppose fA = 3.125 cm and fB = 2.083 cm, giving L = 2.604 cm and feq = 2.5 cm, by Eq. (32). 1.05 cm 30. Then by resonant collisional energy transfer—made possible because the 2.S level of helium is nearly equal to the 3s2 level of neon—step 2 is achieved as excited helium atoms transfer their energy over to ground state neon atoms, raising them to the neon 3s2 level. The irradiance at a point P = 0 and the principal maxima are centered at values for which a = 0, ; p, ; 2p, and so on, c 0 2 f. Or, as in Figure 22b, a parallel ray which refracts at the lens surfaces as if coming directly from the left focal point F of a diverging lens. The scattering of sunlight from oxygen and nitrogen molecules in the atmosphere, for example, is Rayleigh scattering, as is the scattering of light from dense scattering centers—like the droplets of water in clouds and fog—is not. Determine the refractive index of the liquid. Since the effect was discovered in 1893, long before the discovery of the laser, it was well known even before intense optical fields became available. When does this occur? With ultraviolet immersion microscopes, it is customary to replace the oil with glycerine and the optical glass elements with fluorite and quartz elements because of their higher transmissivity at short wavelengths. S1 s a ls S2 r 1 Screen Born, M. To operate as a demultiplexer, the difference in path lengths of the arms of the Mach-Zehnder fiber interferometer must be such that the signal of wavelength l1 constructively interferes upon recombination into Output 1 while light of wavelength l2 constructively interferes upon recombination into Output 2. Then develop an ABCD matrix for propagation to the external beam waist. (17) through (19) in Eq. (20) gives = (t + e^{i\delta} t + r2 + (2E 0) (t^{e^{i\delta}}+ t + r2 + (2E 01 (t^{e^{i\delta}}... - 2kd2 . Boston: Academic Press, 2003. PROBLEMS 1 Derive the Jones matrix, Eq. (15), representing a linear polarizer whose transmission axis is at an arbitrary angle u with respect to the horizontal. 19 Show that, in order to converge flux, the amplitude of a cylindrical wave must vary inversely with kr. High Low High Low High Substrate 7 Low Interference of Light INTRODUCTION Like standing waves and beats, the phenomenon of interference depends on the superposition of two or more individual waves under rather strict conditions that will soon be clarified. 1. 0.001 cm Air 13 The prism angle of a very thin prism is measured by observing interference fringes as in the Fresnel biprism technique. The lad saw better than ever before. The Dispersion Equation The variation in refractive index with frequency, described by Eq. (39), is what we mean by dispersion. On the screen, therefore, in accordance with Eqs. As a result, for every zinc atom added, there are empty spaces in the lattice reserved for an electron. Silver has a concentration of 5.86 * 10^{28} free electrons per cubic meter. 10 Plot the irradiance pattern if the central maximum is proportional to N^2 and the principal maxima are centered at values for which: ... 1985: 54.) 21 Sketch an arrangement using a PCM to project a sharp, high-intensity image of a mask onto the photo-resist layer on a semiconducting chip without using lenses. 5 DOUBLE REFRACTION In the cases depicted in Figure 10b and c, the light propagating through B the crystal may develop a net phase difference between E-components perpendicular and parallel to the crystal's OA, but the beam remains a single beam of light. 7 0, xj 6 0, and m 7 0. Rotator The rotator has the effect of rotating the direction of linearly polarized light incident on it by some particular angle. Spherical Aberration In the paraxial ray approximation, all rays emanating from an object point, after reflecting from a spherical mirror or passing through a lens with spherical surfaces, either intersect at, or to the viewer appear to intersect at, a common image point. 483 Theory of Multilayer Films 20 18 n1 2 16 14 n1 1.8 R (%) 12 10 8 n1 1.6 6 4 n1 1.4 2 Figure 2 Reflectance from a single film layer of index of refraction n1 versus normalized path difference. Residual aberrations are due to errors in the actual fabrication of the correcting plate and because the plate does not present precisely the same cross section, and therefore the same correction, to beams entering from different directions. The quality of the interference pattern in the double-slit experiment depends on the degree of coherence between distinct regions of the wavefield at the two slits. The primary image "observed" by the eyepiece is in this case a virtual object (VO) for the field lens, since its virtual position falls between the lenses. Two polarizing filters acting as polarizer and analyzer are set up with a white-light source behind the pair. Within 1 1 d; 1 c 1 0 0 d 1 What then is the result of the ABCD matrix for this "thin lens"? 10 a. Successive minima are determined in a similar way from other zeros of the Bessel function, as indicated in the table in Figure 8b. The condition of constant phase evidently describes the motion of a fixed point on the waveform, which moves with the velocity of the wave. In Section 10 we discuss, in a bit more detail, the operation of diode lasers. Light from a point object is incident on the convex cylindrical surface from a distance of 25 cm to the left of the lens. Often the first two terms are sufficient to provide a reasonable fit, in which case experimental knowledge of n at two distinct wavelengths is sufficient to determine values of A and B that represent the dispersion. Another type of fiber, the graded-index fiber, is produced with an index of refraction that decreases continuously from the core axis as a function of radius. Assuming Fraunhofer diffraction, what is the slit width? The net effect, in an assembly of oscillating atoms, is to introduce an additional time dependence related to the random deletion of the contribution of one of the oscillators from the net charge oscillation in the medium. Pneumatic chamber Leak Window 2 QUANTUM DETECTORS OF RADIATION V2 (a) Incident radiation Ballasting reservoir Flexible mirror Absorbing film Quantum detectors respond to the rate of incidence of photons rather than to thermal energy. Relating u_c to the entrance angle u_m by Snell's law, λ s = d 2 n1 b - 1 B n0 sin u a (6) For example, in the case of n = 1, l = 600, u = 30°, and d = 50 nm, Eq. (6) gives λs = 152 nm. Electrons behave as though the forces binding them to the nuclei are elastic forces given by Hooke's law, where the restoring force is proportional to the displacement and oppositely directed. Ch. 391. 1941: 488. How does the irradiance at the screen vary, if the contribution of one slit alone is I0? A schematic of such a cell is shown in Figure 2. In discussing attenuation earlier, we pointed out that minimum absorption in silica fibers occurs at around 1.3 mm. For example, a lens of 4-cm focal length that is stopped down to an aperture of 0.5 cm has a relative aperture of A = 4>0.5 = 8. What is the irradiance at the center of the beam 10 m from the beam waist? Figure 14 is a plot of the refractive index versus wavelength for crystalline quartz. Solution By comparison with Eq. (9), k = 3p/m and v = 10p/s. The vitreous humor, essentially structureless, contains small particles of cellular debris that are referred to as floaters. In the amplitude it can be safely approximated by the distance Z between planes, in the phase we use the approximate expression just derived. (New York: Pergamon Press, 1975), Ch. 8) and Robert Guenther. Atomic nuclei are too massive and inner-core electrons too tightly bound to respond to the oscillating E-field at the frequency of light. 1 · 1014 - 1015 Hz). In gas lasers consisting of mixtures of gases, the distinction between host and laser atoms is generally not made. (14) and (15). The cooperative effect of many oscillators tends to cancel the radiation in all directions but the forward (refraction) direction and the backward (reflection) direction. Gaussian Beam Phase Fronts Having discussed the changing irradiance of a Gaussian beam as it propagates, let us now turn to an investigation of the nature of the wavefronts (that is, the surfaces of constant phase) associated with a Gaussian beam. If so, what does this say about R and r? 5 a. At a = 2f 32. In part (a), the optical system is a single aperture A placed in front of a single lens. r Interface Refr a medi cting um n t ut Refracted ray Reflection: ur ui Refraction: sin ut sin ui = constant sin ui ut Figure 1 Reflection and refraction at an interface between two optical media. Since such atoms have a range of velocities relative to a laboratory observer, the emitted waves from an ensemble of atoms emit nearly single-frequency electromagnetic radiation. Using these, the reflectance and transmittance are found to be RTE = (2TE = 0.274022 = 0.075 and TTE = 1 - RTE = 0.925 RTM = and TTM = 1 - RTM = 0.965 r2TM = -0.18662 = 0.035 2 5 EVANESCENT WAVES In discussing the propagation of a light wave by total internal reflection (TIR) through an optical fiber, we mentioned the phenomenon of cross talk, the coupling of wave energy into another medium where it is brought close enough to the reflecting wave. 1 THERMAL DETECTORS OF RADIATION The simplest measurable response of a detector to incident radiation is a rise in temperature, the device is a thermal detector. Although the derivations involve simple algebra and geometry, they are rather arduous. 21 Determine the nature of the polarization that results from Eq. (12) when (a) e = p>2; (b) E0x = E0y = E0 ; (c) both (a) and (b); (d) e = 0. Without the usual paraxial approximation—restricting rays to those making small angles with the axis—one can show that for a small object near the axis, any ray drawn an object point that is refracted at a spherical interface must satisfy the Abbe sine condition, nh sin u = n'h' sin u' (9.30) Here h and h' are object and image size, respectively, and the angles u and u' are the slope angles of the rays entering and leaving the optical media n and n_{2}, respectively. This is the phenomenon of total internal reflection, which occurs at the critical angle u_c = sin-1 1n2 > n1 2. ≈ f so hi hi 43 Geometrical Optics object, a cylindrical lens produces a line image of a point object. A monochromator is used to obtain quasi-monochromatic light from a tungsten lamp. In this case, the region of amplification has a nearly constant gain and is more easily visualized and more dependent on the ASE. Determining the beam waist of a Gaussian beam. En = - 1 Actually, the situation is considerably more complicated than this. Towers adapted the principle of masers to light in the visible region, and in 1960, T. Assume that light of frequency v0 = c/l is input into the cell. 15 Explain how you can use an adjustable circular aperture (iris) and a power meter to determine the spot size w of a TEM00 laser beam at any position along the beam. a fa/2 + fb/2 + 1 y Similarly, Figure 2b represents horizontally polarized light, when letting E0y = 0, wx = 0, and E0x = A. ' E0xei ... A 1 d = Ac d E0 = c iwy d = c E0ye 0 0 3 2 2 2 1 1 linear polarization along x On the other hand, Figure 2c represents linearly polarized light whose vibrations occur along a line Breaking an angle a with respect to the x-axis. About half the beam is lost so that image point U; receives only about half as much light as point V; and U; fades as a result. If the Doppler effect is responsible for this shift, what velocity does it determine for the quasar? This laser is used to pump ... Also, determine its power. 4 B B B A B B B Unless the speed of the charged particle is a significant fraction of the speed of light, the magnitude of the electric force on the particle will be much larger than that of the magnetic force. Find the relative likelihood P 3 = P1 = 0 that a hydrogen molecule will be in its first excited rotational state in thermal equilibrium at room temperature, T = 293 K. At what object distance nearer and farther than the middle row does an unacceptable blur occur if the camera has a focal length of 50 mm and is stopped down to an f/4 setting? Even if the obstacle is not opaque but causes local variations in the amplitude or phase of the wavefront of the transmitted light, such effects are observed. When the wave penetrates into the medium of lesser refractive index by an amount 2d = 1 + u sin 2 u 2p - 1 B n2 (50) the combined Fresnel equations for the small-input irradiance of problem 8, even for an ideal four-level gain medium, it is not true that every pump event leads to one photon added to the electromagnetic field being amplified. 21 A glass plate is sprayed with uniform opaque particles. In this special case, Eq. (3) reduces to B - KSBr = eE or, eliminating Nt with the help of Eq. (2), the static polarization is given by N Ne2E P = KS B (4) 9 Suppose now that E is a harmonic field with a time dependence given B by E = E0e -vt and that the oscillations respond with a similar dependence, B B r = Br -vt. If they are too large, the image is blurred. This time the zones are rectangular strips along the wavefront, as in Figure 7a. 9 The image of the objective formed by the eyepiece is the exit pupil, which locates the position of maximum radiant energy density and thus the optimum position for the entrance pupil of the eye. 6 Show that Eq. (34) follows from Eqs. (24) and (25) again for a and b. K = e - b b r1 r2j) - 12a in -b le f = e - e2 r1j) - 12a1eb - e-b2 2b With the help of Euler's equation, this can be written as 1-b 1-b 1e3 b2 cos(1 r1j) - 12a) 2b + 1 be b2 1e3 12 r2j) - 12a) b where we have expressed the cosine as the real part of the corresponding exponential. The shutter speed must be fast, of course, to capture an action shot without blurring the image. Solution 3 * 108 m>s c = = 3 GHz. 2d 210.05 m2 ntr , we find b. What is the minimum resolvable wavelength at (a) 632.8 nm and at (b) 1 mm? 26 Consider the electromagnetic fields given in 35 a. From the optic chiasma, nerve fibers originating in the right half of each eye extend to the right half of the brain. The amount of light (flux or photon number) that enters the eye is regulated first of all by the iris, with its adjustable aperture, the pupil. 554 Chapter 24 Laser Operation transition to the excited state is resonant with the electromagnetic field so that E2 - E1 1 hv. Assume a substrate of index 1.52. 30 An opera glass uses an objective and eyepiece with focal lengths of + 12 cm and -4.0 cm, respectively. 2 Write out the third-order terms of the polarization for twobeam interaction, where the beams are plane waves having amplitudes E01 and E02 and frequencies v1 and v2 , respectively. In these relations k = 2p>l, and s1 and s2 can be taken to be the distances traveled by each beam along its respective path from its source to the observation point P. For a field point like P, above the plate, the secondary zones divide themselves into two parts, with fewer zones above the axis SOP and (positive a and y) and more zones below the axis (negative a and y). If the wavefront of light from a scene is made to interfere with a coherent reference wavefront, then, the resultant interference pattern includes information regarding the phase relationships of each part of the original wavefront with the reference wave and, therefore, with every other part. When p-type and n-type materials are brought into contact, the usually equal concentration of holes and electrons on opposite sides of the junction induces a diffusion of electrons from the n-type material into the p-type material and a diffusion of holes from the p-type material into the n-type material. In addition, B either case may produce clockwise rotation of E around the ellipse (when Ey leads Ex) or counterclockwise rotation (when Ex leads Ey). 27 a. Now one can show that these intensive are canceled by the decreases that arise from the second consideration, the effect of the inverse-square law. Under what condition is the magnitude of the magnetic force exerted by a harmonic electromagnetic wave on an electron much less than the magnitude of the electric force exerted by the same harmonic electromagnetic wave acting on the electron? In one arrangement for these displays, a mirror is placed after the second polarizing glass sheet in the forward substrate cell. This interval is an absorption band in a given material. To understand the operation of the Mach-Zehnder interferometer, it is helpful to note that beam splitters with real transmission coefficients must have the property that the reflection coefficients from opposite sides of the beam splitter differ by a factor of -1. For lenses with a thickness of 0.025 mm. For the circular zones, the two first-order images are the real and virtual images discussed. What is the distribution of irradiance on the screen near the pattern center as a function of x and y (in mm) and I0 , the irradiance at the pattern center? With the corrective lens, this eye can see clearly print held at any position from 40 to 53 cm from the eye. Other letters are constructed of appropriate size, subtending angles of 5; and 1; for other selected distances, such as 200 ft, 100 ft, 80 ft, and so on, down to 15 or even 10 ft. When the glory is equal to a 0 v0 6p 0 v0 6p 0 v0 2p t0 0 v0 6p 0 v0 4p t 0 v0 6p t v0 Figure 6 Fourier transform of the finite harmonic wave train of Figure 5. Recall that the vectors in Table 1 were formulated by choosing, somewhat arbitrarily, wx = 0. (a) 0.90 cm (b) 5.45 cm, 3 * 20. The input parameters for the ray are its elevation h, angle a, and distance D. These two half-periods—for each original one—contribute light at the focal point r0 = f1>2, out of phase by p with each other. Also calculate the minimum resolvable wavelength in (a) and in (b). Construction of the electric field vector over one period at a fixed plane z = 0 is shown in Figure 1 for the case of (a) linear polarization and (b) circular polarization. Assume that the beams are incident symmetrically on the film's surface. A suitable absorber is a system that is absorbing for low light irradiances but transparent for high light irradiances. What is the stimulated emission cross section σ for this transition? K n0 sin um = n1 sin uc = 2n21 - n22 (4) If n0 = 1, the numerical aperture is simply the sine of the half-angle of the largest cone of meridional rays (rays coplanar with the fiber axis) that are propagated through the fiber by a series of total internal reflections. Helmholtz and L. 50 < 1.81 M 10 0c m 0.5 mm M2 = Intersection of mirrors Figure 27 600 mm 700 nm 45 Glass Problem 12. Spectrum of the light in Figure 7 also assume that the aperture is large enough so that its own boundaries do not appreciably modify the diffraction pattern. (c) When B = 0, the output plane is the image plane conjugate to the input plane and a is the linear magnification. The focal lengths of the objective and ocular lenses are 20 cm and 5 cm, respectively. The amplitude at P becomes a0+2, or half that due to the tiny first-zone aperture alone. Recall that the frequency measured by a detector depends on the velocity of the source of the wave relative to the velocity of the detector. Now and 23% of the corona signal are to be used to complete the experimental procedure. A rotation of 30° is required from spherical aberration at point P except that portion designated by the spinal-length interval ty in Figure 16b. In order for an assembly of atoms or particles to be treated as a blackbody or a graybody, the assembly must be able to emit and absorb a continuous range of frequencies. 501 Fresnel Equations u u u 0 Figure 7 The Fresnel thomb. If only 0.1% of the light is lost at each reflection, over a length of 1 m, this attenuation would reduce the energy by a factor of about 720. For external reflection (light that travels from air to glass, with n1 = 1 and n2 = 1.5, for example, up = 56.3°. The beam radiates from a small circular area of diameter 0.4 mm centered at the laser. 230 Chapter 9 Coherence amplitude of ψ_1 is squared, the resulting curve is the power spectrum, shown as the solid curve in Figure 6. In a Littrow mount, using Eq. (16), the blaze angle must be ub = sin-1 c 1121600 * 10-62 d = 21.1° = 21°06' 211>12002 On the other hand, if the grating is used in a mount with light incident normal to the plane of the grating, then from Eq. (17), ub = 1 2 1121600 * 10-62 sin-1 c d = 23.03° = 23°02' 11>12002 -1 b. More precisely, since it is (B) B Figure 8 One-dimensional autocorrelation E(B2 of a semicircle with radius = 3 as a function of the displacement parameter B. Refracting Telescopes Figures 31 and 32 show two refracting telescope types, producing, respectively, inverted and erect images. The molecules of the liquid crystal in contact with the glass tend to align with the scratches in the sheet. Commercial gratings are usually specified by their blaze angles and the corresponding first-order Littrow wavelengths. Light to be analyzed is focused onto a narrow slit S and then collimated by lens L1 and refracted by the prism P, which typically rests on a rotatable platform whose angular position can be read. If we write N = W>a for a ruled grating width W and incorporate the grating equation for normal incidence, Eq. (11) becomes P = mN = a a sin um W b a l or P = W sin um l (12) According to Eq. (12), the resolution of a grating at diffracting angle um depends on the width of the grating rather than on the number of its grooves. In each case, the rays corresponding to the wavefront are everywhere normal to the mirror surface on reflection. n 1.5 E1 It is desired to project onto a screen an image that is four times the size of a brightly illuminated object. Analyzer TA I E0 y Polarizer co E E0 I0 so TA u 90 180 270 360 u u Figure 3 (Sketch of d) Analyzer Figure 2 Illustration of Malus' law. The shortest distance from A; to B is obviously the straight line A;QB, so the path ADB is the correct choice taken by the actual light ray. We distinguish the case for which ec = p>2 (SA vertical) from the case for which ex = p>2 (SA horizontal). Through the use of a "flash lamp" or another laser, the lasing medium may be excited into its higher energy states. We are perhaps more familiar with the oscillator between the three representative rays are drawn. Pile-of-plates polarizers are especially helpful in those regions of the infrared and ultraviolet spectrum where dichroic sheet polarizers and calcite prisms are ineffective. Spontaneous emission occurs even in the presence of an incident electromagnetic wave that causes stimulated emission. The laser aperture and integrated throughput of the Michelson interferometer make it useful as a Fourier-transform spectrometer. In this case, the irradiance at point P is proportional to the square of the length of the phasor from O to E. The optical system has unit magnification. A photosensitive surface, typically containing alkali metals, absorbs incident photons that transfer enough energy to enable some electrons to overcome the work function and escape from the surface. In general, for several thin lenses in direct contact, 1 1 1 + + + A = f1 f2 f3 (33) Expressed in diopters, the refractive powers simply add: P = P1 + P2 + P3 + A (34) In a nearsighted eye, the refracted (converged) power of the eye is too great, so that a real image is formed in front of the retina. Biological specimens are covered with a cover glass of 0.17- or 0.18-mm thickness. Thus, B B Eloc P B = + Eapp 3e0 B Choosing to retain the symbol E for the applied field leads to B B Eloc P B = + E 3e0 (75) 538 Chapter 25 Optical Properties of Materials Substituting this expression for the local electric field into the right-hand side of Eq. (6) gives P = a B B Ne2 P B b aE + b 2 3e0 - mv - imvg + KS (8) B We can solve for P explicitly by, for the moment, setting the prefactor in Eq. (8) equal to P. The nature of the superposition at P is determined by the path difference between successive parallel beams, r = 2nd cos ut. The shape of the lens is controlled by the ciliary muscle, connected by fibers (zonules) to the periphery of the lens. An electron with energy greater than zero is no longer bound to the proton in the nucleus of the hydrogen atom. Let a = 0.95 and b = 0.05 for a given sheet of Polaroid. Recall that nonlocalized fringes (Figure 6) are, in contrast, formed everywhere. 1 = 3 = the angular spatial frequency is kY = 2p11>d2 = 2p> 31.4>mm. Such edge effects are important, however, only when the aperture itself is very near the aperture itself. needed for Imaging. Applying to the "economy of nature," Fermat supposed instead that the ray of light traveled the path of least time from A to B, a generalization that included Hero's principle as a special case. In this way, a system matrix for the entire optical system can be found that is related to the same cardinal points characterizing the thick lens. Source plane Thin lens L1 at 40 cm from the source plane Aperture A at 20 cm Farther from L1 Thin lens L2 at 10 cm farther from A Image plane Lens L1 has a focal length of 40/3 cm and a diameter of 2 cm; lens L2 has a focal length of 20/3 cm and a diameter of 2 cm; aperture A has a centered circular opening of 0.5-cm diameter. Along directions marked D, on the other hand, the waves are seen to be out of step by half a wavelength, and destructive interference results. Coherence The optical property of light that most distinguishes the laser from other light sources is coherence. A unique image point is not determined by these rays because they have no common intersection or virtual image point below the surface from which they appear to originate after refraction, as shown by the dashed line extensions of the refracted rays. For example, with two such lenses back-to-back, we write the lens equations 1 1 1 = + = w1 s1 f1 1 sw =2 - s2 f2 Since the lens separation is zero in the first lens plays the role of the object distance for the second lens, we may write s2 = - s1 and, adding the two equations, 1 1 1 1 + = + = s1 s2 f1 f2 The reciprocal of the overall focal length f of the pair. These are called zero-order (or sometimes firstorder) planes. We know that each electron so oscillating constitutes a dipole source that radiates electromagnetic energy in all directions, except the direction of the electron oscillation itself. The second experiment is the Fresnel biprism. Since the Fourier transform is an amplitude (not an irradiance) transform, we describe the square wave in Figure 3 by the amplitude of the transmitted light. The shape suggested in the figure is designed to make the focal point of all zones appear at the focal point of a zone whose radius is 0.707 of the aperture radius, the usual choice. A diode laser is essentially a p-n junction whose cleaved edges act as reflecting surfaces that supply the cavity feedback. A ray from the first focal point, F1, is rendered parallel to the axis (Figure 1a), and a ray parallel to the axis is refracted by the lens through the second focal point, F2 (Figure 1b). H e Ne u Ub a N a ub 12 The Diffraction Grating INTRODUCTION In this chapter we give a formal treatment of diffraction due to any number of slits or apertures. Let us use the scaled coordinates xs = 22x>w1z2 and ys = 22y>w1z2. In Figure 9a, the three rays shown originate at a source point S below an interface and emerge into an upper medium of lower refractive index, as is the case of light emerging from water 1n1 = 1.332 into air 1n2 = 1.002. Figure 35 25 cm Problem 15 16 A plano-convex lens having a focal length of 25.0 cm is to be made with glass of refractive index 1.520. In Figure 16a, reflection from the lower surface of BS2 is taken to be r2 = 1 = 12, and that from the upper surface of BS2 is taken to be r2 = 1 -12 = e ip> 12. In an actual system, some channels are devoted to housekeeping functions such as synchronization. In the limiting case of Fraunhofer diffraction, Eq. (7) is simplified by assuming that (1) the obliquity factor is roughly constant over the aperture to be integrated; that is, that the variation of path length is sufficiently small to be represented by exponential functions. In the present chapter we examine, in detail, spherical reflecting and refracting surfaces and, more briefly, cylindrical reflecting and refracting surfaces. The core material—silica, in the case of glass fibers—absorbs in the region of its electronic and molecular transition bands (see Figure 6). The fringe system at the screen then coincide and correspond to the fringes of a single point source. The physical mechanisms underlying their operation will be discussed in the next chapter. 15 A double-slit diffraction pattern is formed using mercury green light at 546.1 nm. When the curvatures of three successive interfaces are perfectly imaged in the gain medium. Fibers can be bound rigidly by fusing their outer coating or cladding. Determine the phase spacing of the developed volume hologram. The interference fringes are now interference surfaces within the emulsion that 379 380 Chapter 16 Holography ES ER I2 Figure 5 Standing wave fringe planes in a volume hologram formed by two plane waves oppositely directed. (a) 1 62 Hunter Optics We wish to show now that this series of bright points on the fringe pattern of the reflection is observable. Using the field as usual as the sum of the electric field of the interfering surfaces is a square root. Often times both of the opposite sides of the object the result that the superposition of the two waves. This rotation of Poincaré sphere. For instance, the eye, the rotation angle of the Poincaré sphere makes the image point determined by the gravitational strain is, therefore, by E2 · Eo. 2p 2p 1100t2 ≈ 1100t11>212 14100 nm (b) 1-2 m r2 14.88 10-7 m = 15.51 0-9 m (c) fc s kes = Using this in the final expression for the detected power, Pdet L P01dg>22 = 110 W2a 5.15 # 10-9 b = 6.5 # 10-17 W 7 This power corresponds to about 160 photons/s and, while small, is easily detected. Generate a table of x, y-coordinates for the surface and plot, together with sample rays. 10 DIODE LASERS Semiconductor or diode lasers have gain media that differ significantly from the atomic and molecular gain media discussed in the preceding sections of this chapter. This mode of polarization, in which the is perpendicular to the plane of incidence and the B-field lies in that plane of incidence, is called the transverse electric (TE) mode. Except for light energy lost by absorption and scattering during passage through the dielectric layers, the percent transmission of the structure is given by T1%2 = 100 - R1%2. (a) 8 cm, 3 × (b) 7.38 cm, 2.6 × 31. Show that Snell's law holds between the first and last media, that is, independent of the intervening regions did not exist. This represents a disadvantage of the Galilean telescope, leading to a restriction in the field of view. The magnitude of the dipole moment for a given material depends on how easily charge is displaced within each of a given electric field. Both the Huygens and Ramsden eyepieces, Figures 25 and 26, incorporate the design feature required by Eq. (39), that is, plano-convex lenses are separated by half the sum of their focal lengths. That is, as many as 80% of the photons incident on a photodiode in the CCD array are converted to signal electrons. What visibility results there if (a) their electric field vectors are parallel and (b) if they are perpendicular? J., Vol. Thus, using Eq. (48), φh = 1 In11>S2 6 g0 2L so L 7 1 1 1 In11>S2 = In a b = 1.5m 2g0 210.00) cm2 10.99210.982 Since the gain cell must fit into the laser cavity, the laser cavity must be longer than 15 cm. = B12N1g1n g2 -1N2 = g1n -1N2 B12N1g1n2 = B12N1g1n2 = B12N1g1n) 211c2 0 (11) 2 Actually, these coefficients depend also on the structure of the enclosure surrounding the atom. For example, since 10 nm is not much larger than the wavelength of visible light. The minus relation in part (a) implies that for the large input-irradiance case of problem 9 every pump event leads to one photon added to the electromagnetic field being amplified. In general, their (complex) electric fields may be expressed by "E1" = E0 e^{i(ks1 - vt)} "E2" = E0 e^{i(ks2 - vt)} (6) where k' = 1v>c2n = 2p>l. If the light is from a He-Ne laser at 633 nm, what is the fringe spacing? Although the actions of stops, pupils, and windows depend quite clearly on the principles of geometrical optics, the details can at times be confusing. Explain their formation. Note that these wavelength components are just barely resolved since the peaks are separated by a FWHM of either dotted curve. Q-switching proceeds in the following time sequence: 1. In an n-type semiconductor, the material is doped with an impurity whose outer shell has one electron more than the outer shell of the atom that it replaces in the lattice. For myopia, the corneal curvature is decreased by removing tissue around the periphery of the cornea, thereby increasing the refractive power of the eye. Similarly, Figure 5g illustrates the situation for corrected near vision under accommodation. 262 Chapter 12 Fabry-Perot Optics efficient multiplexers and demultiplexers that can discriminate between and combine or separate the different wavelength channels must be used. Furthermore, the hologram may contain a number of separate exposures, each taken with the film at a different angle relative to the reference beam and with different wavelengths of light. The Nernst glower behaves like a graybody with an emissivity greater than 0.75. Thus, light of all wavelengths appears in the central or zeroth-order peak of the diffraction pattern. In each case, the OAs of the two prisms are perpendicular to one another, so that an E-component in the first prism, for instance, may become an E? component in the second, with a corresponding change of refractive index. 2 Many practitioners in the field of high-energy lasers use the far-field criterion, L 7 100 (area of aperture>l). Another such ray is evidently OVI, normal to the surface at its vertex point V. (b) Nonalignment of ray BB B fraction is a loss of optical radiation from a fiber. 6 SURGICAL VISION CORRECTION In the preceding section we discussed the correction of myopia and hyperopia with the help of corrective contact lenses or eye glasses. Image and object happen to be at 2f = 20 cm, the center of curvature of the mirror. The far-field divergence angle due to diffraction of a beam passing through a circular aperture of radius r is uniff = 0.61l>r. The transmittance curves can be found from the basic expression for T and the relation between round-trip phase shift d and frequency n. It forms images of a continuum of objects, at distances of a foot to infinity. Also determine the general relationship for the lateral magnification. (Oriel Corp., General Catalogue, Stratford, Conn.) 102 103 104 0 2 4 6 8 10 12 14 16 18 Wavelength (nm) 20 22 24 26 28 141 Microwatts/cm2 nm at 50-cm distance from bare lamp Properties of Lasers Typical spectral irradiance 3.0 2.5 2.0 1.5 1.0 0.5 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0 1.1 1.2 Wavelength (mm) 1.3 1.4 1.5 1.6 1.7 1.8 Discharge lamps The discharge lamp depends for its radiation output on the dynamics of an electrical discharge in a gas. In this technique a phase mismatch dk between the fundamental and second harmonic fields can be compensated for by using a nonlinear crystal with a periodic structure such that the sign of x2 changes every coherence length Lc of the crystal. With Kind Permission of Springer Science and Business Media.) 211 Chapter 12 Interference Interferometry It is interesting to note that the ratio of this maximum wavelength difference to the minimum resolvable wavelength difference is given by the finesse, l>m dlmax = F = clmin 1n>F2 The fact that this ratio is the finesse is not surprising. Classically, Raman scattering can be described as arising from the third-order nonlinear polarization of Eq. (3). In this condition, BP2 - BP1 = AP2 - AP1 = 0 If source B is moved below A, the fringe systems separate until, at a certain distance s, where BP2 - BP1 = e l 2 r P2 - 1/2 B Figure 30 Light from each of two point sources A and B reach points P1 and P2 in the radiation with wavefronts of different shapes at the screen. Let us now develop a more explicit understanding of the formation of the secondary peaks. As the screen is moved Figure 31 Formation of a line image ... 30 Two fibers ... An object is placed in front of a convex cylindrical lens of ... This graphical procedure must be modified to accommodate any number of component waves of the same frequency, as shown in Figure 4 for four such waves. 2 A BRIEF LOOK AT ABERRATIONS All aberrations lead to a blurring of an image formed by an optical system, thereby frustrating the optical designer intent on producing an ideal image— that is, a faithful point-by-point re-creation of corresponding object points. Thrierr, Atlas of Optical Phenomenon, Plate 18, Berlin: Springer-Verlag, 1962.) 6p 129 284 Chapter 11 Fraunhofer Diffraction When b = mp, with m = ; 1, ; 2, A, as shown. The superposition of waves at a point where their electric fields are orthogonal, for example, does not yield the same result as the case where they are parallel. Laser Operation Figure 18 shows the band structure in the junction region. How far can the mirror be moved from zero path difference so that fringe visibility is at least 0.85? The light diffracted from a plane grating must be focused by means of a lens or concave mirror. For an arbitrary incident wavefront, as shown in Figure 16c, the amplitude "1r2 is complex and includes the amplitude and phase factors that describe its deviation from a plane wave. Determine the beam spot size w(z) at the left and right cavity mirrors. The heat flow into the gas causes an increase in gas pressure, which is typically detected by the deflection of a flexible mirror attached to the cell, as shown in Figure 3. This fundamental linewidth is sometimes called the Schawlow-Townes linewidth.5 In practice, the linewidth of a laser is significantly larger than the limit set by the mixing of spontaneous emission into the laser output. Any distribution, however, shows detailed structure in its own shadow that is quite unexpected on the basis of geometrical optics. minimum adjacent to the second-order maximum of 600-nm light? These wavelengths are but two in a continuum described by the spectral width, dl, of the source, usually chosen as the width of the source's spectral output at half-maximum, as shown. Fast and slow axes are induced in a plane normal to the applied field, as shown in Figure 3. We consider each interval of length ds as a source and calculate the result of all such sources by integrating over the entire slit width b. Thrierr, Atlas of Optical Phenomenon, Plate 32, Berlin: Springer-Verlag, 1962.) the rectangular slit considered earlier. 1 RATE EQUATIONS Rate equations relate the population densities (number of atoms or molecules per unit volume in a given energy state) to the properties of an electromagnetic field incident on the atoms or molecules. Example 6 Do a ray trace for two rays through a Rapid landscape photographic lens of three elements. If the beam divergence is expressed by the diffraction angle uD = l>D, with D the beam diameter, then Eq. (27) may be written n = tanS uD where t is the time for the sound to cross the optical beam diameter. Operationally, assessment of resolving power or visual acuity of the eye is measured in different ways. (c) Production of interference fringes in the region of superposition of two coherent and collimated beams intersecting at angle 2a. Wavelengths shorter than 360 nm are filtered from the light. The behavior of these functions is illustrated in Figure 2a. As illustrated in Figure 12a, light may be linearly polarized along any line that is perpendicular to the direction of B wave propagation. Light of photon energy 5 eV likely be absorbed by a hydrogen atom originally in its ground state? r 0 Gabor zone plate I2 I1 Reference beam 11 Spherical waves s Figure 9 Problem 1. Of course, the holographic system must be vibration-free to within a fraction of the wavelength of the light during the exposure, a condition that is easily satisfied when high-power pulses of very short duration are used to freeze undesirable motion. 28 A single transmission grating is designed to have a nonzero diffracted fourth order. Where is the lens and how long a focal length must it have? And what is the first-order diffraction angle for 820-nm light? Arbitrarily a single Wollaston prism of fixed Fresnel interferometer. Refractive indices for the film and substrate are 1.38 and 1.52, respectively. Unobstructed Wavefront The irradiance in the Fresnel diffraction pattern associated with different apertures are often compared to the irradiance Iu associated with an unobstructed wavefront. The next-best solution is to use a graded index (GRIN) fiber, which is described next. The Fourier transform of a nonperiodic function requires instead a continuous frequency spectrum g(k). As with all waves, the frequency of an electromagnetic wave is determined by the frequency of the source of the wave. Since an ionized (freed) electron can have any energy, the range of energies associated with a free electron can be any continuous. Finally, we may also vary both path length to produce frequency changes. Show that: 1. It is not, for example, surprising that the only contribution from the origin due to local variations in the quantity n - n ff . (29) and (30), that as the angle of incidence approaches the critical angle, φ_c must approach a value of 2 in the TE mode and 2/n in the TM mode. This can be accomplished by propagating a pump laser field through the fiber. This means that the induced grating is essentially stationary relative to the light wave. 5 ALLOWED MODES Not every ray that enters an optical fiber within its acceptance cone can propagate successfully through the fiber. Typically, at observation points of interest, the electric field amplitudes of the two interfering waves are the same in magnitude, so that any phase difference between them will show up in the resulting field. Incidentally, the magnifying power of this eyepiece, given by 25/f, is therefore 10 *. Determine where and at what angle the rays cross the optical axis. 6 BLAZED GRATINGS The absolute efficiency of a grating in a given wavelength region and order is the ratio of the diffracted light energy in the sample wavelength region. For the case of myopic astigmatism, Figure 7a, the corneal surface is evidently less sharply curved in the horizontal meridian [power = 45.00 D] than in the vertical meridian [power = 46.00 D]. The angle between the dashed lines is 60°. Various choices of the radii of curvature, while not changing the focal length, may have a large effect on the degree of spherical aberration of the lens. We have said that the fluorescence lines from a weakly excited gas originate from spontaneous emission and so have linewidths that are the same as the width of the transition line. Using these focal lengths, the lens and the optical axis form a triangle. We conclude that the analysis of plane waves propagating in a homogeneous dielectric requires in general that the propagation constant k be a complex number. Since every data unit is recorded throughout the volume of the hologram, in unique holographic fashion, damage to a portion of the hologram, although affecting the signal-to-noise level of the reconstructed image, does not affect its reliability. A 50-mW He-Cd laser emits at 441.6 nm. The transmittance of a fixed-length Fabry-Perot interferometer considered as a function of a variable-wavelength-input field has transmittance peaks of FWHM equal to ¢lmin = l>mF and a peak separation (that is, a free spectral range) equal to ¢lmax = l>m. In so disregarding the effectiveness of the overlapping wavelets, Huygens avoided the possibility of diffraction of the light into the region of geometric shadow. 16 A ray is incident on a boundary between glass of index 1.50. An optical window allows electromagnetic radiation to fall on the p-type side of the junction. In addition, since the laser beam has a high degree of directionality, it behaves (near the beam waist at any rate) like a bundle of parallel rays coming from a point object at infinity. (The Ealing Corp.) Chapter 6 Properties of Lasers 100 100 Xenon-cathode tip Relative spectral emission 90 90 80 80 70 70 60 60 50 50 40 40 30 30 20 20 10 10 0 0 200 250 300 350 400 450 500 550 600 650 700 750 800 850 900 950 1000 1050 1100 1150 Wavelength (nm) Figure 8 Spectrum of emission for xenon compact arc lamp. For example, a thin lens of n = 1.50 and f = 10 cm may result from an equiconvex lens of s = 0 1r1 = 10, r2 = -10 cm2; a plano-convex lens of n = + 1 r1 = 5 cm2; a meniscus lens of s = + 2 1r1 = 3.33, r2 = 10 cm2. The output power is then, approximately Pout L IoutA = 15?0 W>cm2210.1 cm22 = 57 W d. Clark Jones, "A New Calculus for the Treatment of Optical Systems," Journal of the Optical Society of America, Vol. 18 The subscripts x and y refer to the surface of a lens. It is standard practice in a course in electricity and magnetism to show that the bound-charge density is related to the polarization by B (f) = -§ # P (16) B The quantity § similarly represents the current density and can arise from B B B both free and bound charge, as indicated by J = Jb + Jf. Since these modes have different dependences on the transverse coordinates x and y, they are referred to as different transverse modes. Note that the approximate number of round-trips, N#, that a portion of the light field makes before exiting the cavity is, then, N# L ty 1 = t 211 - r22 (46) It is useful to note that Eqs. In pure water the light does not scatter sideways but propagates only in the forward direction. Linear-electrooptic effect for any of the known elements, with more than a thousand laser transitions in gases alone. 400 Chapter 18 1 0 0 Figure 5 a0 L a1 Matrix Methods in Paraxial Optics where the input data y0 , a02 at point 0, we wish to predict values of y7 , a72 at point 7 as output data. High Diffracted light beam Undeflected light beam A k Index of refraction RF signal Piezoelectric transducer ks Moving sound waves at speed y K Nonlinear Optics and the Modulation of Light value. Chromatic aberration in thesis lenses can be effectively reduced by using multiple refractive elements of opposite powers. The line image is virtual at a distance of 11.11 cm on the object side of the lens and 2.80 cm long. When red He-Ne laser (632.8 nm) is used, the measured rotation is 900 min. Taken as a whole, Table 1 includes lasers whose wavelengths vary from 193 nm (deep ultraviolet) to 10.6 mm (far infrared); whose power outputs vary from 0.1 mW to 20 kW; whose beam divergences vary from 0.2 mrad (circular cross section) to 200 mrad (elliptic cross section); and whose overall efficiencies (laser energy out divided by pump energy in) vary from less than 0.1% to 20%. Both object and screen are then moved to positions on the screen that is three times the size of the object. Obviously, fringes should be present in all the space surrounding the holes, where light from the holes is allowed to interfere, though the pattern is intercepted by the screen at their edges: a multiple E01 = + E01 + E01 1 = r2ei-id (22) Here, d = 2kd is the round-trip phase shift. Optical Electronics, 3d ed. The vertically polarized beam incident on the Pockels cell is transmitted as a horizontally polarized beam. The lifetime t of an energy level is defined to be the inverse of the total decay rate from the level so that, in the present case, t3 = 1, k3 t2 = 1, k2 and t1 = 1 k10 The lifetime of a level is the time for the population density of a given level to decay to 1>e of its initial value, when the decay process is the only process that occurs. Suppose that E is chosen in the original direction of B and B is rotated accordingly in the same direction. Let the n0 be the phase of ordinary spherical waves, along the z-axis, is given by R2 = R1 + 1z2 - z12 (35) Similarly, the basic law of propagation for the laser beam follows from Eq. (14) and is given by q2 = q1 + 1z2 - z12 (36) an equation identical to Eq. (35) except that R has been replaced by q. Slit aperture Edge of geometrical shadow 435.8 nm S T For the near-field diffraction pattern of a straight edge, calculate the irradiance of the second maximum and minimum, using the Cornu spiral and the table of Fresnel integral values given. Extinction of a region of the spectrum by interfering films of l>4 thickness is, of course, more effective if the amplitudes of the two reflected beams are equal. The maximum half-angle of this cone is evidently related to the critical angle of reflection wc . Using Gaussian optics, determine the final image of the system, after two refractions (a) by a three-ray diagram and (b) by calculation. Determine the Cauchy constants A and B in the long wavelength region; from the Cauchy relation, find the dispersion of the prism at 656.3 nm. Born, Max, and Emil Wolf. Thus, dlmax may be called the (wavelength) free spectral range fsr of a Fabry-Perot interferometer. The y-coordinate is identical in either system. (28) and (29). Further, the factor s>hn¡ has a dimension of inverse time and so is a rate. Using a beam splitter (BS) by means of a thin film, a semitransparent layer of metallic or dielectric film, deposited on glass. This position is just the point of intersection between the optical axis and a line drawn from the lens to the aperture stop AS. 2 GAUSSIAN BEAMS If we now examine the electromagnetic character of a typical laser beam, we would find that its wavefronts are essentially spherical surfaces with long radii of curvature that increase as the beam advances along the propagation axis. If the amplitudes due to contributions from any number of zones can be determined from such a drawing and the relative irradiances compared. 3 Find the resultant of the superposition of two harmonic waves in the form E = E0 cos(a - vt2 with amplitudes of 3 and 4 and phases of p>6 and p>2, respectively. What is the ratio of irradiance of the evanescent wave at 1 mm beyond the surface to that at the surface? Complementary metal-oxide-semiconductor (CMOS) detectors and charge-injection devices (CID's) are two additional, increasingly important, digital imaging technologies. These lines were among those that appeared in the solar spectrum studied by J. The medium for which n' ? n¶ is therefore levorotatory. This dependence is noted by proceeding the term with the word spectral and by using a subscript l or adding the l in parentheses. Proceeding, Eq. (52) does indeed give the known experimental result that these problems approximate the plane of polarization. Show that on the grating equation (3), sin a = ml, so that sin u = 11 - 2 sin a 2 a = 1 10-4 Thus: u1 u = 14.5° and cos u1 = 0.968. By now we are familiar with the factor in it representing the diffraction envelope of a single slit, of irradiance. Center and the edge of any groove is zero. When j = 2, the next two slits are included, whose edges are located at Fraunhofer Diffraction 1 2 1 - 3a - b2 and 1 21 - 3a + b2 below the origin and 121 3a - b2 and 121 3a + b2 above it. When j = N>2, all slits are accounted for. TM 20 30 40 50 60 70 80 90 up 33.69 u1 41.81 up 56.31 Angle of incidence u This condition is also evident in the vanishing of FN in Figure 3 and the vanishing of the numerator of Eq. (28). (a) Standard MachZehnder interferometer with two mirrors, two beam splitters BS1 and M2, and two 50-50 beam splitters. Hailey, M. Before constructing representative rays, we first find the image distance and lateral magnification of the image, using Eqs. Thermal detectors are generally characterized by a slow response to changes in the incident radiation. We may think of P1 and P2 as two slits that propagate light to a screen, as in the two-slit interference experiment. The beam irradiance may be viewed. (27) to (30), Eq. (24) takes the form, E0 + Er1 C g0El0 - Er12 S = C cos d lg1 sin d i sin d Er1 m21 cos d gsEt2 m12 Et2 dc d m22 gsEt2 (31) where in the last equality we have used the generic form of the transfer matrix given in Eq. (25). The requirement is that every ray from O, like OPI, refracts and passes through image I. (b) Modulated wave representing Eq. (33) at x = x0 . As we show in Example 4, a corrective lens of a single power (as used in reading glasses) will not restore clear vision of both near and distant objects for a person who has lost accommodation. On the other hand, 13 Robert Guenther, Modern Optics (New York: John Wiley and Sons, 1990), ch. 14. More information can be sent by optical fiber when distinct pulses can be transmitted in more rapid succession. Without affecting the order of validity of this approximation, we may replace, in the last exponent, the term r2>2z2 by r2>2z2, leading to the following expression describing the phase fronts of a spherical wave: kr L kz + kr2>2r2 - 1ant Spherical wave near z-axis (30) Now a Gaussian beam described by Eq. (24) has phase fronts that satisfy the condition kz + kr2>2R1z2 - tan-11z>z02 = constant R(z) 2z0 z0 z0 Figure 5 Variation of the radius of curvature R with distance z along the optical axis. It is assumed to be 25 nm in an optical material. The quantity 1>RLz2 = z>z2 + z02 is given as the correct distance from the lens and on axis. In effect this lens must produce images 5 to 30 m with an acceptable sharpness. e-s ± (e - 1p 8) Richelson found that the cadmium red line (643.8 nm) was one of the most ideal monochromatic sources available, allowing fringes to be discerned up to a path difference of 30 cm in a beam-splitting interference experiment, such as with a Michelson interferometer. Nevertheless, the complementary aspects of particle and wave descriptions of light remain, justifying our use of one or the other when appropriate. The laser light thus contains essentially a pure single wavelength. Therefore, the first three bright spots produced by a Ronchi ruling with transmitting slits of width 0.25 mm, as in Figure 2. Unpolarized light incident from the left is scattered by a particle at the origin O. Plots of the population densities of the two levels and the population inversion as functions of light irradiance are given in Figure 3. What is then the difference percent reflection from the film layer? Determine the amplitude, frequency, wavelength, speed, and direction of the component waves whose superposition produces this result. It was called a maser. The field depicted in Figure 2a is represented by E0x = A and E0y = 0. If the input plane is located at distance x is the object space and the new output plane at distance s¿ in image space. 6 Chapter 1 Nature of Light l = 6.626 * 10-34 J # s h = 4.19 * 10-13 m = 0.419 pm 1.58 * 10-21 kg # m>s and from Eq. (5): y = 11.58 * 10-21 kg # m>s2213 * 108 m>s22 = E.482 * 10-13 J = 2.95 * 108 m>s For the photon, with m = 0, we get instead, from Eq. (6): p = E.482 * 10-13 J = 1.61 * 10-21 kg # m>s c 3 * 108 m>s from Eq. (7): l = h = 6.626 * 10-34 J # s = = 0.412 pm p 1.61 * 10-21 kg # m>s and from Eq. (8): y = c = 3.00 * 108 m>s There is another important distinction between electrons and photons. Cavities with higher loss rates have lower quality factors. It remains to determine the proper Bragg angle of the grating. Consider next the action of the Ep , or TM, component (Figure 4b). New York: Academic Press, 1977. Apertures, in its broadest sense, is an opening defined by a geometrical boundary. This quantity is plotted in Figure 3 for different temperatures. Thus gratings with more slits direct a greater fraction of the energy emerging from the slits towards the positions of the peaks of the order-m maxima than do gratings with fewer slits. The treatment of a system in which a significant population is transferred to an excited state is mathematically more complex. We let laser light of irradiance I and frequency n¿ be incident on the atomic medium. Solids and liquids sometimes have continuous bands of energy. Interpret the terms as done in the discussion of a hologram of a three-dimensional subject. In this section we present an alternative method that can also be used to determine the loss rate of a laser cavity. Assuming that the prism angle A and refractive index n are given, then the stepwise calculation for a ray incident at an angle u1 is as follows: u1 = sin-1 a sin u1 b n (7)-d1 = u1 - a (8) u2m = A - u1e (9) u2 = sin-1n sin u2m (10) u2e = u1 + u2 - u1e - (10) u2e (11) The variation of deviation with angle of incidence for A = 30° and n = 1.50 is shown in Figure 10. When the laser is turned on, the irradiance is very small and so the gain coefficient g1n2 takes on its small-signal value g0n2. Images I1 and I2 result from single reflections in the two mirrors, but a third image I3 results from sequential reflections from both mirrors. One way to confirm this is to compare the color of stars, as they appear visually, to their photographic images made on color film using a suitable time exposure. (7) and (8). Determination of MTF at various spatial frequencies, like the curves shown in Figure 10b, allows a more complete evaluation of system performance than resolution alone. The rate of spontaneous emission is independent of the spectral energy density of the electromagnetic field. 9 THIN LENSES We now apply the preceding method to discover the thin-lens equation. The original shape of the pulse, y = f(x,z), does not vary but is simply translated along the x direction by the amount yt at time t. Until recently, a photographic film or plate was the most common image-recording medium. Chapter 26 Davis, Christopher C. The spatial extension of the cycle of light due to each object point maps out an image whose sharpness depends on the diameter of the individual circles. If the air-film thickness now changes by an amount ¢t = d, the order of interference m changes accordingly, and we have 2¢t = 2d = 1m2l where we have set m = 1 for an air film. Amplitude-division interferometers instead use some type of beam splitter that divides the initial beam into two parts. This image will be affected by spherical aberration, as discussed earlier, to a degree determined by the displacement y of the extreme rays of the pencil. (Photo from M. In practice, s V and angles u are approximately equal. An angle equals is expressed in units of length, so tan b, both plotted in Figure 3. This sort of arrangement is in fact used for detectors with a relatively small number of pixels. Both rods and cones are composed of stacks of disks, with the disks of the long rods thinner than those of the shorter cones. However, as suggested by Figures 1, 2, and 3 and in contrast to a spherical wave, the center of curvature of a Gaussian beam wavefront changes as the beam propagates along the z-axis. That is, E1t2 = e2 + t0 + ct2 = PE1et, t2tE120 , t02 For example, for a plane monochromatic wave traveling in the + z direction encountering no changes in optical media, PF1cz, ct2 = E1rt + t2, ct + t2 E0e1rt + ct2 - k1z0 + cz2] = e1ivct - kz2 = E1z0 , t02 E0e1iv0 - kz02 (17) Mirror 1 El d Mirror 2 E1 ET ER r, t, t z Figure 9 Generalized Fabry-Perot interferometer consisting of two mirrors with reflection and transmission coefficients r and t. In 1 2A u l B u a Figure 16 Representative grating slits illuminated by collimated light at angle. ... and the limit is applied to Fraunhofer diffraction of this fiber. However, for a round-trip set r1 and r2 , as a surface (lens) rr. (a) Pm = 67°33', no c ; TE: no p, n o c (b) TM: no p, n o c (c) Xmj TM: no p, n o c (c) Pm = 67°33', no c = 2Z°24'; TE: no p, c = 24°24' 13. 59 Chapter 27 Characteristics of Laser Beams where R1 and R2 are the radii of curvature at incidence and refraction, respectively, and f is the focal length (see Figure 8). When the first half-period zone has been blocked, the last amplitude is advanced by p relative to the first and ends at T. The amount of rotation caused by optically active liquids is much less by comparison. The CO2 laser is one of the most versatile and efficient laser systems, capable of CW power outputs ranging from mW to MW with efficiencies ranging from 10% to 40%. Typically, the cover glass index is 1.522 and the oil index is 1.516, providing an excellent match. For the present, we assume monochromatic light, which has its own characteristic refractive index in the prism medium. The technique was introduced by Wander Lugt in 1963. Infrared radiation is also used in optical fiber communication systems and in a variety of remote control devices. (33) and (34) may then be calculated using K1 = P1D r1D - 1 and K2 = P2D r2D - 1 (46) Finally, the radii of curvature of the lens faces may be determined. Throughout this chapter, we will assume that effective path-length differences between interfering beams that originate from the same source are much less than the coherence length of the source. The doublet is an equiconvex lens of radius 50 cm and is made, 1.50, and central thickness 20 mm, followed by a matched meniscus lens of radii -50 mm and -87 mm, index 1.8, and central thickness 5 mm. p2 let n1 up Production of Polarized Light The active medium of a gas laser is often bounded by two Brewster windows, located at the ends of the gas plasma tube. P enters the prism at face AB and departs at face AD, making an angle of 90° with the incident direction. A voltage placed across an individual segment causes the gas in the cell to ionize that is, causes a plasma to be formed and to subsequently emit ultraviolet light, which in turn strikes the phosphor coating causing the emission of red, green, or blue light. G1 and G2 represent two-phase coupled generators radiating coherent ultrasonic waves. Further, when n = 7 0, the crystals are said to be uniaxial positive, and when this quantity is negative, uniaxial negative. New York: Academic Press, 1972. 8 ELECTROMAGNETIC WAVES The harmonic waveforms discussed so far can represent any type of wave disturbance that varies in a sinusoidal manner. All that is required in principle is that the electrons do not have sufficient energy to interact with an incident electromagnetic wave in one direction than in an orthogonal direction. This requirement allows for a determination of the required etalon length d: etalon nfsr = d 6 c 7 6 GHz 2d 3 * 108 m>s = 2.5 cm = 216 # 109 Hz2 1 2 # 1010 Hz Laser Frequency Stabilization When embedded within a feedback loop, the Fabry-Perot cavity can be used to provide state-of-the-art frequency or length stabilization. The normalized form must be divided by 2X2 + R2 + C2 . 18 A certain argon-ion laser can support lasing over a frequency range of 6 GHz. Estimate the number of standing wave modes that might be in the laser output if the laser cavity is 1 m long. 13 Waves on the ocean have different velocities, depending on their depth. 58 Show that elliptical polarization can be regarded as a combination of circular and linear polarizations. In traversing the lens, ray undergoes two refractions and one translation, steps for which we have already derived matrices. The exact distribution of the electric field pattern across the wavefront of the emerging laser beam, and thus the irradiance pattern of the lens. The shapes of the sections of the object and image planes are not ... then we expect ... an in sin u = n' sin u'. The overlap of the spots of the images can be compared. Interference fringes are seen on a screen 1 m away. This circular image is what we customarily view. What is the effect on the fringe separation of an emulsion with a high refractive index? 8 Use a computer to calculate and plot the reflectance curves of Figure 4. 5 Referring to problems 3 and 4 and Eq. (2), construct an energy-level diagram for the H2 molecule that shows the first vibrational and rotational states associated with the ground electronic state of the molecule. The normalized correlation function g(t), sometimes called the degree of coherence, can be simplified by expressing 11P and 12P in terms of the optical path of the source field. The detection point is located 50 cm on the other side of the aperture plane. Values of M¿ for fused quartz over the same range are only about 1 to 4.5 ps/nm-km. The transmission coefficient of a single propagating mode is then given by the product of the Fourier transform of the aperture. For example, the spectral lines of Figure 5 and of a hollow cathode are referred to the center of curvature of the rays. To the same, the magnitude of the field at the screen depends on the limitation of aperture. At each point of a ... mode ... Suppose ... a wavelength of 632.8 nm ... a collimating lens of focal length ... is the hologram grating frequency? A beam of 4-mm diameter ... the position ... for an angle of incidence of 50°. ... Table ... for 100 d ... n ... The irradiance of the central spot ... In Figure 10, the results of such calculations ... single layer of index ... on glass of index 1.50 ... a light beam ... the wavefront ... at a distance of 5 m? ... using ... 1.50 ... ... the propagation direction and wave polarization relative to the crystal axes. ... R k R# 441 Aberration Theory spherical surface, centered at C, that separates media of refractive indices n1 and n2 . In the case considered, a concave mirror, R, is negative. (19) and (20) for constructive and destructive interference are reproduced. The object is an extended object of transverse dimension bo, Jenkins and Harvey E. The composite phasors in Figure 5b begin at the start of the phasor al and terminate at the end of the phasor an for any number of contributing Fresnel zones. In the high-loss state, the population inversion grows, which in turn leads to an increase in spontaneous emission. In other words, what is the focal length of a single refracting surface? Using Eq. 20, the distances from the central spot are ky (a) E E0 sin kj Y1 = (1) 1488 * 10-92 10.42 If r = 112 m = 9.76 * 10-4 m = 0.976 mm 0 0.2 * 10-3 X5 + (3) 1488 * 10-92 10.42 I0 r = 2.93 * 10-3 m = 2.93 mm = 132 0.02 * 10-3 E h. The first ray reflects back along itself; the second reflects off at P as if from a plane tangent at P, satisfying the law of reflection. Phys., Vol. Calculate reflectance for (a) TE and (b) TM modes at angles of incidence of 0°, 30°, 50°, 70°, and 90°. We know that the time difference between paths, relative to the average coherence time t0 of the source, is crucial to the degree of coherence achieved. 15 Enlarge the optical system of Figure 15 to include an object space to the left and an image space to the right of the lens. The edge of the shadow is clearly not sharp. At each point, the amount of light passed by the mask depends both on the amount of light available in the image and the transparency of the mask at that point. In the above case, rays from axial point object O that encounter the lens are symmetrically placed points P converge at axial point N, while rays from O that encounter the lens at points Q converge at axial point M, L, and M. The spatial coherence of the wavefield is also perfect since along each wavefront the variation of the relative phase of the field is zero. (Hint: Think of the oil layer as an intermediate thin lens.) 23 A small object is placed 20 cm from the first of a train of three lenses with focal lengths, in order, of 10, 15, and 20 cm. A wide-angle lens is a short focal length lens with a large field of view. Specialize Eqs. Finally, we mention Doppler weather radar, in which a source emits an electromagnetic pulse, which is scattered by a particle. Then the radar receives waves moving raindrops and other particulates. To provide quality images, the ocular is corrected to some extent for aberrations and, in particular, to reduce transverse chromatic aberration. In Figure 10, let the region labeled "optical system" include any number of reflecting and/or refracting surfaces, of any curvature, that may alter the direction of rays leaving an object point O. Figure 7b shows a comparable condition and prescription for hyperopic astigmatism. If the fast and slow axes of the QWP are interchanged, a similar calculation shows that the result is left-circularly polarized instead. The real image formed by the objective lens of a microscope, for example, serves as the object O that is viewed by the eyepiece, whose angular magnification contributes to the overall magnification of the instrument. Then yf = Ay0 , independent of a0 . Techniques involving interferometric and electronic servo-control have been used to enhance the precision of the most modern ruling engines. In a modern version of this experiment, a laser is typically used to illuminate the two holes. 11 The total path difference executed by a Fourier-transform spectrometer operating in the infrared is 2.78 mm. f -1.00 m b. In this case, Eq. (42) reduces to normal incidence quarter-wave thickness R = n n0ns - n21 b n0ns + n21 2 (43) From Eq. (43), it follows that a perfectly antireflecting film can be fabricated with a coating of l>4 thickness and refractive index n1 = 1n0ns . Determine the radii of the first and second bright rings. For example, as a typical ratio of the diffraction grating size by a star on the focal plane of the objective. If one pattern is translated relative to the other, however, the bright points of the image no longer all coincide with the transparent regions of the mask, and light throughput and correlation are reduced. The resulting hologram effectively contains a large number of images mapping the motion of the vibrating surface. The inverse transform, as in Eq. (6), is EA1x, y2 = A P1kX , kY2e -i1kX x + kY y2 dkX dkY 1232 0 (18) Within the approximations made, we have shown that the Fraunhofer diffraction pattern is the Fourier transform of the aperture function described by EA1x, y2. (c) Spontaneous emission initiates stimulated emission. Similarly, we consider the observation screen to be effectively at infinity by using a lens on the exit side of the slit, as shown 269 Fraunhofer Diffraction I 0 x b s u b u a = ?u a ¿ u u f Figure 1 Construction for determining irradiance on a screen due to Fraunhofer diffraction by a single slit. Figure 1 shows the polarization as a function of the electric field for the linear case and the deviation from linearity due to the nonlinear terms. Using the conditions specified in Figure 21b and m c must be physically equivalent, so that we can write E1 = Ir2 + t12E1 and I = Ir12 + tr2Et or t1 = r2 + t2 (42) (43) Equations (42) and (43) are the Stokes relations between amplitude coefficients for angles of incidence related through Snell's law. grating having a groove separation of 1.0 mm. 24 Determine the number of photons in a 0.5 light pulse ... (If the reference beam is white light, the continuously displaced images due to different spectral regions of the light overlap and produce a colored blur. Which component now limits the cone of light rays? The first condition is satisfied by making the angle of incidence relative to N¿: ub = um + ub , or ub = ui um - 2 (13) N The second condition requires that the angle um satisfy the grating equation, ub = N ml = 1sin ui + sin u2 (14) Figure 6 Relation of the blaze angle ub to the incident and diffraction angles for a reflection grating. These energy levels shift in the periodic table from those occupied by which excited atoms in a state of high excitation above the ground state by radiation from transferring energy to lower energy levels, producing and random radiation waves. In this chapter we define more precisely the area of nonlinear optics, describe and categorize some nonlinear phenomena, and discuss some of their practical applications. Parrent, Mark J., and George B. Thus we should have both P2 = e0x21 + E22 and - P2 = e0x21 - E22 Because the E-field is squared, P2 = - P2 , which can only be true if P2 = 0. Light is incident on the unsilvered side. further than s¿ from the lens, one sees an unfocused blur that has the general shape of the lens aperture. (a) The lens is ... either the rectangular or circular... a distance ... 1 LINEAR POLARIZATION ... the Jones vector representing ... incident ... on a second polarizer ... the ray matrix ... MATHEMATICAL REPRESENTATION OF POLARIZERS: JONES MATRICES Various devices can serve as optical elements that transmit light but modify the state of polarization. For the q-expression, we write 1 g- 2ikx 1 1 0w g2 b = = - C1 a 2 g w q 0x g w (53) We can show, with the help of Eqs. Incorporating Eqs. Notice that low-order modes—m small—correspond to w = 90°, or ray directions that are nearly axial, and high-order modes—m large—correspond to rays that propagate with w near wc , or at steeper ray angles. (a) l d d (b) 201 Optical Interferometry as suggested in Figure 7b. Recalling that a dipole oscillator radiates only weakly along directions making small angles with the dipole axis 11 sin2 u2, we conclude that only a fraction of the Ep component of original light (TM component) appears in the reflected beam. Now the ratio of reflective object-to-image distance, however, is the lateral magnification of the image. 11 Calculate the reflectance of white light and the transmittance at the angles of incidence 0°, 10°, 45°, and 90°. London: Butterworths, 1980. z b where u is the angle of incidence and n is the ratio n2>n1 . Meyer-Arendt, Jurgen R. The plate thickness is 1.50 mm. The fringes are observed to be separated by 0.03 cm. Solving Eq. (21) for the phase fronts that satisfy the condition kz - tan-11z>z02 = constant. Solving this expression for d, gives ud. The equation is positive when O is to the left of V, corresponding to a real object. Ideally, when the real object, ND, falls at the position of the first lens, rays emerge from the converging lens of at a position giving a virtual magnified image at infinity. (a) Why couldn't light of one wavelength be used? At the first refracting surface, of radius R1 , n2 n2 - n1 n1 + = s1 s1 R1 (23) and at the second surface, of radius R2 , n1 n1 - n2 n2 + = s2 s2 R2 (24) We have assumed that the lens faces the same medium of refractive index n1 on both sides. Using Eq. (44) in Eq. (43) yields the indicative relation Iout = T18s a 1q0 - gth2L 1 - S (45) Let us obtain an expression for the threshold small-signal gain coefficient gth in another fashion. The fusion by the brain of two distinct images into a single image is referred to as binocular vision. However, for a round trip the amplitude is to the n'z , where r is complex, requires further investigation. In an alternating electric field, however, electronic and ionic polarization effects can occur over a certain amount of energy from the incident radiation, the energy that the electrons radiate in turn and the energy of interaction with neighboring atoms that shows up as thermal energy. This relativistic expression3 for kinetic energy EK approaches 12 my2 for y V c. The circular fringes of equal inclination no longer appear; in their place are seen fringes of equal thickness. Arrays of diode lasers allow for relatively high average power devices. Secondary maxima result because a uniform phase difference between waves from adjoining slits causes the phase diagram to curl up, with a smaller resultant. 2 Two harmonic light waves with amplitudes of 1.6 and 2.8 interfere at some point P on a screen. The forms of the lineshape functions given in the preceding paragraphs are appropriate for those relatively common cases in which either homogeneous broadening or Doppler broadening is dominant. Photosensitive crystals, such as potassium bromide with color centers or lithium niobate can be used in place of thick-layered photoemulsions. Similarly, one typically replaces the wavelength l1 appearing in Eq. (37) by its nominal value l. A third DHDM design challenge that has been met is the limiting of dispersion so that separating the wavelength channels by 0.8 nm provides isolation sufficient to prevent cross talk between channels over long hauls. Also plot the corresponding transmittance. Although the length is along the spiral remains fixed, its placement at different positions along the spiral determines a different chord length and thus a different irradiance. The answer to this question is not always obvious. These photons constitute the laser beam. Determine the apparent position and magnification of the fish's eye when its actual position is (a) at the center of the bowl and (b) nearer to the observer, halfway from center to glass, along the line of sight. For example, suppose an amplitude A P = at is measured at P when a circular aperture coincides with the first Fresnel zone. 17 a, Optical activity is easily measured using two linear polarizers originally set for extinction, that is, with their TAs crossed in perpendicular orientations (Figure 17). In terms of the the x, y-coordinates of the first ... and the Fourier ... at the image point ... are related to each other by ... as ... E0 ... p ... and the final ... between ... . In the Fresnel ... the specifications of this four-element lens, including an intermediate air space of 3 mm, are as follows, with distances in mm: R1 R2 R3 R4 R5 R6 = = = = = = 17.5 5.8 18.6 - 12.8 18.6 - 14.3 1d 13 14 15 = = = = = = 2.9 1.3 3.0 1.1 1.8 n1 n2 n3 n4 n5 = = = = = 1.6489 1.6031 1.5154 1.6112 Focal point Incident radiation Posterior capsule Retina Cornea 4 mm 19 10 mm 20 mm Optics of the Eye INTRODUCTION In this chapter we discuss the optics of the eye. The corneal curvature, typically 8 mm, can be measured by an instrument called a keratometer. The basis of the chromatographic/spectrometer field vector B is then B E * B determined to ensure that the direction of is the direction of wave B B E -field propagation k. These dimensions cannot be satisfied, however, unless the two slits have merged into one and are unable to produce interference fringes. Other vertical sections would produce other points along the focused line image AB in the same way. NX-ray = 6.63 * 10-16 J>s Power = = 0.33>s. New York: Cambridge University Press, 1986. Complete coherence: t = 0 and ƒ g ƒ = 1 Ip = I1 + I2 + 2 2I1I2 cos vt Imax = I1 + I2 + 2 2I1I2 = 4I0 , Imin = I1 + I2 - 2 2I1I2 = 0, V = for equal beams for equal beams 4I0 = 1 4I0 3. 24 Newton's rings are viewed both with the space between lens and optical flat empty and filled with a liquid. Employing the Newtonian form of the lens equations, determine the appropriate distance of the object and screen from the lens. The diffraction grating equation is first generalized to handle light beams incident on the grating at an arbitrary angle. Thus the beam represents a reconstructed wavefront from the subject, making the same angle a relative to the reference beam. Let the gain medium be homogeneously broadened and have length L = 10 cm and a saturation irradiance (at the lasing frequency) of IS = 2000 W>cm2. The total angular deviation d of the ray 61 Optical Instrumentation A d d2 d1 u1 B u1 u2 u2 n n=1 Figure 9 Progress of an arbitrary ray through a prism. 548 Chapter 25 Optical Properties of Materials nI Figure 3 Angular frequency dependence of the refractive index nR and the extinction coefficient nI for copper. Figure 30 illustrates the optical components in a standard microscope and the detailed processing of light rays through the instrument. Two thick glass or quartz plates are used to enclose a plane parallel "plate" of air between them, which forms the medium within which the beams are multiply reflected. Explicitly, IF = r2 + s2 + rsei1vt + u2 e-i1vt + w2 + rsei1vt + w2 e-i1vt + u2 IF = r2 + s2 + rsei1u - w2 + rse-i1u - w2 (7) The scaled irradiance IF describes the hologram and is a function of x and y and so varies from point to point on the film plane. In this case we can set N1 + N2 = NT (16) where NT is the total population density of the atoms in the medium. In triangle CPO, the exterior angle a = u1 + w. To solve it, we make an "educated" guess1 at a solution, motivated in part by the cylindrical symmetry (about the propagation direction) that we expect in the electric field and in part by the complex nature that the solution U(x, y, z) must exhibit. If the lens surfaces are flat, a prism is formed, and paraxial rays can no longer produce a unique image point. Additionally, we have chosen to write the temporal part before the spatial part in arguments of the sine functions of Eqs. Thus, 1 c d 22 i 1 LCP Similarly, if Ey leads Ex by p>2, the result will again be circularly polarized light with clockwise rotation leading to right-circularly polarized (RCP) light. To excite the Cr+3 impurity ions in the ruby rod, Maiman used a helical flashlamp filled with xenon gas. Smith, W. Said Arthur Zajonc, in his lead article titled "Light Reconsidered": Light is an obvious feature of everyday life, and yet light's true nature has eluded us for centuries. Employing as a spectrometer an instrument such as the Michelson interferometer, these advantages derive both from the use of a large aperture at signal input and from the presence of the entire spectrum at signal output. Light emerges from a source slit S, as shown, that is p = 20 cm from the diffracting slit. Suppose that in a small region of the film the thickness is such as to produce constructive interference for wavelengths in the red portion of the spectrum at some order m. The phase angle w arises from the angle a between the film plane and the plane wavefront of the reference beam, as indicated in Figure 2b. If the pinhole in the screen is 3 mm from the central white fringe, where would one expect dark lines to show up in the spectrum of the pinhole source? In the intermediate case of Fresnel diffraction, the diffraction pattern is essentially an image of the aperture, but the edges are fringed. Boston: PWS-Kent Publishing Company, 1990. 28 Draw phasor diagrams illustrating the principal maxima and zero irradiance points for a four-slit aperture. If the interface XY were not present, the Huygens construction would produce the wavefront GI at the instant ray CF reached the interface at I. This cavity loss rate, often called the cavity decay rate and given the symbol ≠, must be compensated for by the gain medium in order to maintain steady-state laser operation. If the signal field input into the fiber has a frequency that is near the peak of the Raman bandwidth, it will strongly stimulate the Raman process and transfer energy from the pump field into the signal field. The blurring diameter in the image is chosen to be d = 0.04 mm. Recall that in the making of a hologram, no lens is used, and the presence of the reference beam is essential. As the irradiance in these four modes grows, gain saturation further reduces the gain coefficient, causing still more modes to drop below threshold. Assume normal incidence and stacks of (a) 2; (b) 4; (c) 8 double layers. In many real gain media the gain broadening is due to a complicated mix of many physical processes and is difficult to model accurately. Ordinary polarization by scattering is generally weak and imperfect and so is not used as a practical means of artificially producing polarized light. To understand how these rays locate the conjugate image point P¿ that marks the tip of the image, it is useful to imagine that these three rays arrive at the eye of one viewing the image. For this wavelength, determine the threshold in watts of power. Thin replicas made from a submaster are mounted on a glass 302 Chapter 12 The Diffraction Grating or fused silica blank and a highly reflective overcoat of aluminum is added. Ensure that far-field diffraction is invalid in this case. (21) and (22), therefore, l b dn = a b a b ¢l d dl or the minimum wavelength separation permissible for resolvable images is 1¢l2min = l b1dn>dl2 (23) The resolving power provides an alternate way of describing the resolution limit of the instrument. A case in point is the suppression of low spatial frequencies, or high-pass optical filtering, to enhance the contrast in a photograph. Note that if C1 = C2 = 0, which is necessarily true when m = n = 0 (see Eq. 56), then g1j2 = h1h2 = 1 and we recover the cylindrically symmetric Gaussian-beam solution. 17 Find the number of standing wave cavity modes within the gain bandwidth of the argon ion laser of problem 16 if the laser system uses a resonator with flat mirrors separated by a distance d = 0.5 m. If the incident light is linearly polarized along the x-direction, as in Figure 17, it may be resolved into left- and right-circularly polarized light. Rays 1 and 3, in the left vertical section of Figure 31, focus at A; rays 2 and 4 in the right vertical section focus at B. If the screen were to contact the mirror at M¿, the fringe at M¿ would be found to be dark. What is the speed of the galaxy relative to the earth? Consequently, light rays from a single point O form a blurred image along the line segment containing M and N. Typically, a computer-controlled argon-fluoride excimer laser—of wavelength 193 nm— directs UV radiation onto the cornea in order to remove microscopic amounts of tissue at strategic locations. PROBLEMS 1 What is the angular separation in second order between light of wavelengths 400 nm and 600 nm when diffracted by a grating of 5000 grooves/cm? Fringes formed as in Figure 13 are also) (b (a) P S3 S2 S1 Lens Film Figure 13 Interference by a dielectric film with an extended source. The resultant transmitted or product light in this case must again be vertically linearly polarized light. 414 Chapter 18 Matrix Methods in Paraxial Optics intersects the refracting surface at P, where it is refracted into a medium of index n¿, cutting the axis again at I. As illustrated earlier in Figure 3, decreasing the spot size w0 of the beam at the waist causes the beam to diverge more rapidly as it leaves the waist, leading to a smaller Rayleigh range. The range of frequencies required to modulate a carrier for a single telephone channel is only 4 kHz, whereas the bandwidth of an FM radio broadcasting station is 200 kHz. A commercial TV broadcasting station, which must communicate both sound and video signals, uses a bandwidth of 6 MHz. The great information-carrying potential of a light beam becomes evident when we calculate the ratio of carrier frequency to signal bandwidth, a measure of the number of separate channels that can be impressed on the carrier. The theory presented in this chapter allows us to describe this phenomenon quantitatively. 4 BIREFRINGENCE: POLARIZATION WITH TWO REFRACTIVE INDICES Birefringent materials are so named because they are able to cause double refraction, that is, the appearance of two refracted beams due to the existence of two different indices of refraction for a single material. Solution The system matrix, for input and output reference planes at the two surfaces of the lens, is, then, M = P2PP1 = C 1 0 0 1.5 1 SC 0 3 1 -0.5 SC 1 1.5132 0 1 S 1.5 or 2 3 M = D 1 6 2 T, with Det1M2 = 1 1 The relations in Table 2 then give values of p = - 6 cm, q = 4 cm, r = 0, s = - 2 cm, f1 = - 6 cm, and f2 = 6 cm. The entrance window delineates the lateral dimensions of the object to be viewed, as in the viewfinder of a camera, and its angular diameter determines the angular field of view. A possible arrangement is shown in Figure 6. One is struck with the correspondence between R(z) for ordinary spherical waves and q(z) for Gaussian spherical waves in the defining equations. Explain their occurrence. We will return to each of these points in the following discussion. Other commonly used laser media and their operating wavelengths are listed in Table 1 at the end of this chapter. Solution The focal length of the ocular is found from fe = - fo 15 = = 2.5 cm M -6 The eye relief is the distance of the exit pupil from the eyepiece. LEDs provide narrow spectral emission bands, as is evident in Figure 10. Further, measured from the input and output planes, the distances r and s locate the principal points, and the distances y and w locate the nodal points. Clearly, plane waves, which have planar wavefronts that are infinite in extent, are approximations to real waves, which have limited extent in directions that are transverse to the propagation direction. S1 u u S2 11 Fraunhofer Diffraction INTRODUCTION The wave character of light has been invoked to explain a number of phenomena, classified as "interference effects". the analyzer is oriented at 90° relative to the TA of the polarizer, the light is effectively extinguished. Of the four principal layers that make up the retina—there are in fact ten layers visible with an electron microscope—the second layer below the surface contains the photoreceptors, the light-sensitive rods and cones. One component advances in phase by ¢w and the other lags in phase by ¢w while traversing the crystal of length L, so that their relative phase on emerging is given by £ = 2 ¢w. An enlarged, virtual image (not shown) is formed by the diverging rays leaving the system, as seen by an eye looking into the eyepiece. Bellingham, WA.: SPIE Optical Engineering Press, 1989. (c) Photograph of the diffraction image of a rectangular aperture with b 6 a, as in the representation of Figure 5a. Using Eq. (23) then gives kY = 2p 1m>d2. (a) l>4–l>4; n1 = 1.65, n2 = 2.1. (b) l>4 – l>2: n1 = 1.38, n2 = 1.6. (c) l>4 – l>2: n1 = 1.38, n2 = 1.85. Solution Using Eq. (20), R1 = 211213021632.8 * 10-72 = 0.0436 cm Since Rn r 1n, n increases by a factor of 104 when Rn increases by a factor of 102. Determine the required angle of the crown prism and the resulting angle of dispersion between the C and the F rays. Graphic techniques are used to actually draw the optical system and to trace the ray's progress through the optical system on the monitor.3 Ray-tracing procedures, such as the one to be described here, are often limited to meridional rays, that is, rays that pass through the optical axis of the system. When optometrists prescribe corrective eyeglasses for conditions of myopic or hyperopic astigmatism, they generally identify three numbers. We now derive the relationships between the distances defined in Figure 11 and the system matrix elements. Material Dispersion Even if modal distortion is absent, some pulse broadening still occurs because the refractive index is a function of wavelength. We will use this in generalizing the aberration calculation to include off-axis imaging. This discussion of thermal equilibrium will form a useful background for a discussion of the laser, in which neither the gain medium nor the electromagnetic field is in thermal equilibrium with its surroundings. What power contact lens is needed to correct the far point of this eye? (a) A lineshape function g1n2 (left axis) and a broadband spectral energy density r1n2 (right axis) are shown. by a single lens. The solid guidelines, above and below the z-axis, represent the locus of points for which the beam's electric field irradiance in a transverse direction is equal to 1>e2 of its value on-axis. 16 A nonreflecting, single layer of a lens coating is to be deposited on a lens of refractive index n = 1.78. 9 The energy density of red light of wavelength 660 nm is reduced to one-quarter of its original value by passage through 342 cm of seawater. Chapter 20 Grum, Franc, and Richard J. In fact, these energy levels typically have a narrow but finite width ¢E that arises from the inevitable interaction of the atom with its environment. Correction, with glasses using a lens placed 1.5 cm from the eye, requires that this person see objects at the normal near point (25 cm) clearly. We see that when the frequency of the square wave is larger (more closely spaced rulings with smaller d), the fundamental frequency in the Fourier spectrum is also larger, and the separation Y1 = lf>d is increased—a fact that should already be familiar from our study of the diffraction grating. 24 A half-wave plate is placed between crossed polarizer and analyzer such that the angle between the polarizer TA and the FA of the HWP is u. Coherent sources S1 and S2 are the two virtual images of point source S, formed in the two plane mirrors M1 and M2 . It is important to note that the fields being superposed are proportional to the source field evaluated at different times. This rapid movement of the carriers produced in the intrinsic region decreases the response time of the detector. 449 Aberration Theory 5 ASTIGMATISM AND CURVATURE OF FIELD Aplanatic optics is still susceptible to two closely related aberrations whose wave aberration terms can be combined to give h¿ 2r212C22 cos2 u + 2C202. Problem 17. considered negative. 574 Chapter 26 Laser Operation Gate Gain Mirror Pulse Mirror Figure 15 A mode-locked laser system. 3 What is the energy, in electron volts, of light photons at the ends of the visible spectrum, that is, at wavelengths of 380 and 770 nm? In a similar manner, we may write, for the wavefront point O, a¿1O2 = 1POP¿ - PBP¿2opd = c1BO24 = cb4 (21) If the point Q is referred to the optical axis OC, an off-axis aberration function a(Q) may be expressed as the difference between the axial aberrations at Q and O found previously. Suppose the largest acceptable diameter is d, as shown, such that all images within a distance x of the precise image are suitably "in focus." The depth of field is then said to be the interval MN in object space conjugate to the interval M¿N¿, as shown. Chapter 15 Feynman, Richard P., Robert B. Insert a 10 * beam expander in the beam at a distance z = 30 m past the focused beam waist. Figure 25 0.25 mm 10 cm Problem 19. Determine (a) the numerical aperture of the fiber; (b) the acceptance angle (or maximum entrance cone angle); (c) the number of reflections in 3 ft of fiber for a ray at the maximum entrance angle, and for one at half this angle. What is the luminous intensity of the lamp? Show that group velocity can be expressed as 6 One hundred antennas are putting out identical waves, given by E = 0.02 cos1e - vt2 V>m The waves are brought together at a point. (New York: McGraw-Hill Inc. At the input face of the fiber shown in Figure 3a, œ n0 sin um = n1 sin um C n0 n2 F E n1 A (3) n0 w B wc u⬘m w um D B A (a) Ls u⬘ d u⬘ um u B (b) 3 Other rays, the skew rays, do not lie in a plane containing the central fiber axis. c d 1 5 d. Then for the x2 term of the polarization to be 1% of the linear term, the electric field amplitude E0 must satisfy the relation x2E 20 = 10.012x1E0 or E0 = 10.012x1 10.01212.252 = = 2.25 * 1010 V>m x2 10-12 m>V This electric field strength E0 corresponds to an irradiance of I = 1 1 e0cnE 20 = 18.85 * 10-12213 * 108211.52 2 2 12.25 * 101022 W>m2 L 1018 W>m2 = 1014 W>cm2 3 P. Thus the cell can appear bright or dark depending upon whether or not a voltage is applied across the cell. The theoretical justification for this relation can also be found in Kirchhoff's derivation. Cvijetic, Milorad. The interference factor 1sin1Na2>sin a22 goes to zero when the function in its numerator 1sin1Na22 goes to zero but the function in its denominator 1sin a2 does not. The limit of resolution is already set in the primary image. The first few zeroes, and maxima of the normalized irradiance I>I0 = 12J11g2>g22 are listed in Figure 8b. The result expressed by Eq. (7), however, still involves approximations, requiring that the source and screen distances remain large relative to the aperture dimensions and that the aperture dimensions themselves remain large relative to the wavelength of the optical disturbance. This means, by Eq. (8), that in the region of l = 500 nm, spectral components as close together as 0.0125 nm can be resolved. The velocity of the higher-frequency carrier wave in the resultant waveform of Eq. (33), as well as that of the lower-frequency envelope wave, can be found from the general relation for velocity, y = nl = v k (35) The velocity of the higher-frequency carrier wave in the wave form of Eq. (33), is known is the phase velocity, yp = vp kp = v1 + v2 v k1 + k2 k (36) where the final member is an approximation in the case v1 v2 = v and k1 k2 = k for neighboring frequency and wavelength components in a continuum. For example, an ultrasonic wave hologram can be used in place of medical X-rays and a radar hologram can be read with visible wavelengths. Which orientation(s) would you use to make a quarterwave plate? An optical topography of the cornea, taken prior to either procedure, identifies the regions of the cornea that need to be reshaped in order to make the needed corrections to the refractive power of the eye. 4 1 2 3 5 6 45 Geometrical Optics B Virtual vertical line image B A Real vertical line image A (a) (b) Figure 30 Formation of line images by cylindrical lenses for light incident from a distant object. A high degree of light coherence is necessary in interferometry and holography, which are both discussed later in this text. Ingalls, Albert G. (30) and (31), gives dl2 = 1dC1y222 + 1dS1y222 = c cos2 a py2 py2 b + sin2 a b d dy2 2 2 or simply, dl = dy (36) 324 Chapter 13 Fresnel Diffraction S(y) 1.5 0.7 0.6 E 0.5 1.0 0.4 0.3 2.0 0.2 0.8 0.7 0.6 0.5 0.5 y 0.5 0.1 0.4 0.3 y G 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.2 0.1 0 0.1 C(y) 0.2 0.3 2.0 F 1.0 0.4 E⬘ 0.5 0.6 Figure 12 The Cornu spiral used to construct the irradiance in a Fresnel diffraction pattern. 15 Consider an ideal four-level gain medium in a ring cavity like the one of Figure 8 but with R1 = R2 = 1 and R3 = 1 - T3 . The reflectance given in Eq. (53) represents the maximum reflectance at the wavelength l0 , for which the layers have optical thicknesses of l0>4. The GRIN fiber reduces the pulse-broadening effect of modal distortion in this case by a factor of 292. 39 A plano-concave cylindrical lens is used to form an image of a point object 20 cm from the lens. (b) Difference in the phase between the two waves described in (a). 1 THE GRATING EQUATION A periodic, multiple-slit device designed to take advantage of the sensitivity of its diffraction pattern to the wavelength of the incident light is called a diffraction grating. The mode-locked pulse is the low-loss mode of a cavity that is loss modulated once each round-trip. Of course, the cylinder axis can be oriented at any angle. Plane wavefront Laser beam Spherical wavefront Propagation z-axis Beam waist Converging lens that resemble the field distribution shown in Figure' 1. The Jones vector for vertically linearly polarized light 0 is then simply C 1 D . The laser resonator, then, in addition to acting as a feedback device, also acts as a frequency filter. By introducing a narrow "exit slit" in the screen, one has a type of monochromator that where h is the height and s the "width." (Hint: Remember how to complete a square? The object distance is less than the focal length. Coherence is a measure of the degree of phase correlation that exists in the radiation field of a light source at different locations and different times. 91 Optical Instrumentation 10 A prism of 60° refracting angle gives the following angles of minimum deviation when measured on a spectrometer: C line, 38°20¿; D line, 38°33¿; F line, 39°12¿. The gas is most often xenon. At what values of V and £ (greater than zero) is the transmittance zero? (c) Penta prism; pentagonal cross section. The eyeglass prescription is Rx: + 2.00 - 1.50 * 180. How many data points must be taken over the scan to avoid aliasing within this range? All that is needed to produce the phase-reversed replica on reflection is a concave spherical mirror whose curvature exactly matches that of the wavefront at incidence. Returning to Eq. (31), we need next the sum S: S = 2b N>2 sin b Re a ei12j - 12a b j=1 Expanding the sum, we find S = 2b sin b Re [eia + ei3a + ei5a + Á + ei1N - 12a] b The series in brackets is a geometric series whose first term a and ratio r can be used to find its sum, given by aa 1e2ia2N>2 - 1 eiNa - 1 rn - 1 d = b = eia c r - 1 eia - e -ia e2ia - 1 Using Euler's equation, this can be recast into the form 1cos Na - 12 + i sin Na i1cos Na - 12 - sin Na = 2i sin a - 2 sin a whose real part is 1sin Na2>12 sin a2. These instances of elliptical polarization are illustrated in Figure 4 for ¢w = p>2 and ¢w = 3p>2. Show that in this limit and for an ideal four-level gain medium, IL - I0 = hn¿R2pL b. The complicated effects of all the microscopic contributions to the resultant field by the charges in the material can, for certain purposes, be simply described by macroscopic material parameters, the optical constants of the material. Other eyepieces have also been designed to achieve higher magnifications and wider fields. For orders m Z 0, therefore, the grating separates different wavelengths of light present in the incident beam, a feature that accounts for its usefulness in wavelength measurement and spectral analysis. Example 3 For wavelengths in the visible spectrum, the index of refraction of a certain type of crown glass can be approximated by the relation n1l2 = 1.5255 + 14825 nm22>l2. Sunblock and sunscreen lotions are intended in part to block harmful UV-B radiation. This mix has an index of refraction of about 1.3 and a third-order nonlinear susceptibility x3 of about 10-20 m2>V2. For example, spectral radiant flux is denoted by £ el1l2 The total radiant flux is then determined by integration over the wavelength region of interest: l2 £e = ›Ľ£ el1l2 dl l1 3 OPTICAL REPRESENTATION OF THE EYE As we have seen, the normal biological eye is a near spheroid, some 22 mm from cornea to retina. 11 A beam of linearly polarized light is changed into circularly polarized light by passing it through a slice of crystal 0.003 cm thick. The center of the stopband can be shifted by depositing layers whose thickness is l>4 at another l. Note carefully that a photon of resonant energy E2 - E1 can also stimulate absorption from level E1 to level E2 , thereby losing itself in the process. Waveguide dispersion leads to a variation of neff with l for a fixed-diameter fiber, even in the absence of material dispersion. This is true even when two points along a source slit are not mutually coherent. An electromagnetic disturbance that propagates through space as a wave may be monochromatic, that is, characterized for practical purposes by a single frequency, or polychromatic, in which case it is represented by many frequencies, either discrete or in a continuum. (a) Alignment with the field. In our account of the developing understanding of light and photons, we will be content to sketch briefly a few of the high points. (b) Edge view of (a). In a linear system, these elementary irradiance patterns are simply additive. Calculate the focal length of the secondary convex mirror and the angular magnification of the instrument. Because information can be reduced to such tiny dimensions and the crystal can be repeatedly exposed after small rotations that take the place of turning pages, it is said that all the information in the Library of Congress could theoretically be recorded on a crystal the size of a sugar cube! Information may, of course, be recorded in digital form and thus read by a computer, so holographic storage offers a means of providing computer storage. The flap, hinged along one edge, opens like the page of a book to reveal the underlying layers. O. Photodetector (b) order to, for example, determine the difference in wavelength of two closely spaced wavelength components in the input to the Fabry-Perot cavity. In 1924, he published his speculations that subatomic particles are endowed with wave properties. This being the case, calculate the net fraction of the TE mode transmitted through a stack of 10 such plates relative to the incident irradiance I0 . y 2 Problem 24. Chs. 578 Chapter 26 E pc (a) Spontaneous emission E pc (b) Stimulated absorption E pc (c) Stimulated emission Figure 18 The interaction of an electromagnetic field with a semiconductor gain medium. 34 A spherical interface, with radius of curvature 10 cm, separates media of refractive index 1 and 43 . 2 The threshold of sensitivity of the human eye is about 100 photons per second. Linearly polarized light transmitted through a collection of such molecules creates forced vibrations of electrons that, in response, move not only along a spiral but necessarily around the spiral. Junction Photodiodes One of the most common types of photodetectors is the semiconductor photodiode. Shown there is the image of an off-axis point, formed by a single lens. d that can be supported by the cavity to discrete values. What is the radiance of the laser? This leads to the phenomenon called polarization mode dispersion, which can limit the maximum bit rate of transmission through fibers designed for highspeed communications. We assume further that the film thickness is of the order of the wavelength of light, so that the path difference between multiply reflected and transmitted beams remains small compared with the coherence length of the monochromatic light. One such solution is $n\Delta L$ = 950.011 = 950.5002 (b) Ouput 2. Note and carefully explain your observations. Another application of the device as a beam deflector to initiate lasercavity dumping is illustrated in Figure 14. The irradiance is now Ee r 1 A2 (28) Most cameras provide selectable apertures that sequentially change the irradiance at each step by a factor of 2. As in the spherical mirror case, the result is a blurred line image along the line segment containing M and N. 24 Why is a Nd:YAG laser system that uses a diode laser as a pump more efficient that a Nd:YAG laser system that uses an arc lamp as a pump? 180 Chapter 7 Interference of Light P S S1 S2 Figure 14 Interference by a dielectric film with a point source. 3 23S … … Energy (eV) 19.8 Upper laser level for 0.6328 mm line Pump energy 4 Spontaneous decay to ground level 17.4 2 3 4 5 1s (b) Once the population inversion has been established and a photon of nearly resonant energy hn¿ E2 - E1 passes by any one of the N2 atoms in the upper laser level (step 3), stimulated emission can occur. The resulting chemical action provides further free electrons to continue the reduction process, with the latent image acting as a catalytic agent to further action. It can be shown that the restriction of data to a finite window xw limits the resolution of the spectral distribution so that the minimum resolvable wavelength interval is given by ¢l = l2 xw (43) Relative intensity (a) (b) (c) Path difference Figure 12 Interferograms produced by a Michelson interferometer using different light sources. By contrast, the small transverse extent of laser beams allows a lens or mirror to intercept essentially all of the power in the beam. 50, 1982: 990. 8 Determine the maximum core radius of a glass fiber so that it supports only one mode at 1.25 mm wavelength, for which n1 = 1.460 and n2 = 1.457. 61, No. 12 (Dec. From Eq. (26) it is obvious that a given f may result from different combinations of r1 and r2 . An Introduction to Electrooptic Devices. c d 3 Figure 13 Problem 13. Mica and quartz are commonly used as retardation plates, usually in the form of thin, flat discs sandwiched between glass layers for added strength. A text is scanned, for example, for the presence of a particular letter or word. For diamond, n = 2.42. (36) and (37), is plotted in Figure 6. Teich, Fundamentals of Photonics. For example, for small angle a, a = - y0 y (27) where the negative sign indicates that the ray intersects the input plane below the axis. Figure 3 One type of photomultiplier tube structure. The fiber itself has refractive index n1 , the encasing medium (called cladding) has index n2 , and the end faces are exposed to a medium of index n0 . In (a), a real object is positioned in air, 30 cm from a convex spherical surface of radius 5 cm. The lens merely intercepts a larger solid angle of light when the distance is small. If the aperture is a zone plate with every other zone blocked out and with the radius of the first zone equal to R1 (found in (a)), determine the first three focal lengths of the zone plate. By Eq. (15) or Eq. (16), d2 £ 12 = LdA1dA2 cos u1 cos u2 r212 and the total radiant power at the entire second surface due to the entire first surface is, by integration, £ 12 = L cos u1 cos u2 dA1 dA2 3 3 A1 A2 (17) r212 By adding powers rather than amplitudes in this integration, we have tacitly assumed that the radiation source emits incoherent radiation. PEDROTTI, S.J. LENO M. The image must be in focus and reasonably free from aberrations over the entire area of the film in the focal plane. Consider a simple translation of the ray in a homogeneous medium, as in Figure 5. The image of the top of the object arrow is located by two rays whose behavior on reflection is known. (d) Laser. The small asymmetric output aperture leads to highly divergent nonsymmetrical output beams, as indicated in Figure 17. Matrix Methods in Paraxial Optics 399 Solution Use the equations for the thick lens in the order given: 11.52 - 1211.52 - 1.332 1 1.52 - 1.33 1.52 - 1 4 = f1 11-252 11+252 111.522 1+2521 -252 or f1 = - 35.74 cm to the left of the first principal plane. The product of this cosine factor and the overall fixed amplitude 2E0 may be regarded as the slowly varying amplitude of the resultant wave. 61°4′ ; 28°56′ c = 32.9°, p = 61.5°, p' = 28.5° 1.272 (a) 2.55% (b) 0.233% (c) 4.26% (d) 1.26% (a) 2.01%, 2.10%, 5.23%, 100% (b) 2.01%, 1.91%, 0.274%, 100% 617 12. If the lens is rotated about its optical axis, the line image also rotates, remaining always parallel to the cylindrical axis. Recall that in the process of stimulated emission, each photon added to the stimulating radiation has a phase, polarization, energy, and direction identical to that of the amplified light wave in the laser cavity. Cathode-Ray Tube (CRT) Displays The cathode-ray tube or CRT display was until recently used in nearly all televisions, computer displays, and video monitors. Later, Strong used ruled metal coatings on glass blanks. The larger the actual object, the less precise is its image. For example, light output from a single-mode laser can be fed into a stabilized Fabry-Perot cavity adjusted to allow maximum transmission of this frequency of the laser light. Notice that in the Galilean telescope the exit pupil falls inside the eyepiece, where it is inaccessible to the eye. 3, 9. For this reason, fringes produced by a variable-thickness film are called fringes of equal thickness. Depending on the location of the object point and the ray angle, many of these rays are blocked by the limiting apertures of lenses and mirrors or by physical apertures intentionally inserted into the optical system. Gas Atomic Lasers By an atomic laser we mean one in which the upper and lower lasing levels are different electronic states of one of the atoms in the gain medium. Proceeding, we can form the irradiance at P as, IP = e0c81E1P + E2P229 = e0c58E21P9 + 8E22P9 + 28E1PE2P96 e0c 8E1E2 + E…1E…2 + E1E…2 + E…1E29 = I1P + I2P + 2 (24) where, as before, the brackets denote a time average. If the function representing the transmission of the mask alone is E21x, y2, then the light transmitted through the mask is the product function E11- x, - y2E21x, y2. g(v) 2 1 2 1 2 1 2 1 2 1 v v0 (a) E2 2 1 2 1 2 1 h Radiation E1 Atom After (b) Stimulated emission In 1916, Einstein showed that the existence of thermal equilibrium between light and matter could be explained by positing but three basic interaction processes. If the phase difference between the vibrations is other B than 0 or p, the resultant E-vector traces out an ellipse rather than a straight line. These components experience different refractive indices and different speeds through the crystal. Notice that rays from both wavefronts, at their point O of tangency on the optical axis, reach the same image point I. What is the angle u? A common application of this technique is found in the cemented "doublet" lens. The separation of the principal points is the same as the separation of nodal points, that is, r - s = y - w. 90 Chapter 3 Optical Instrumentation f 5 cm 2 cm 2 cm 5 cm 2 cm Object AS 10 cm Figure 37 2 Repeat problem 1 for an object 4 cm high, with a 2-cm aperture stop and a thin convex lens of 6-cm focal length and 5-cm aperture. 336 Chapter 14 Matrix Treatment of Polarization the case a = 0° and a = 90°. The sum of cosine terms in Eq. (16) then approaches zero as N increases, because terms are equally divided between positive and negative fractions ranging from - 1 to + 1. 3 Consider the following mathematical expressions, where distances are in meters: 1. It is useful to keep in mind the situation depicted in Figure 12a, in which a nearly monochromatic field of frequency n¿ and irradiance I is incident on a sample of atoms that have two levels of energy E1 and E2 that are nearly resonant with the incident light so that E2 - E1 L hn¿. 34. The maximum irradiance in these planes produces, after film development, planes consisting of excess free silver, which function as partially reflecting planes. On emerging, a phase difference of p>2 results in circularly polarized light. Such a calibration procedure is useful, for example, in absorption spectroscopy. Recall that linearly polarized light is equivalent to a combination of right- and left-circularly polarized components. The dispersion, defined as dn>dl, is then approximately, using Cauchy's formula, dn>dl = - 2B>l3. To test an optical system properly, objects having both high and low spatial frequencies are required. If l1 is the shortest detectable wavelength in the incident light, then the longest nonoverlapping wavelength, l2 , in order m is coincident with the beginning of the spectrum again in the next higher order m + 1, or ml2 = 1m + 12l1 The free spectral range for order m is then given by lfsr = l2 - l1 = l1 m (3) The free spectral range is the maximum wavelength separation, ¢lmax , that can be unambiguously resolved in a given order. Note from Figure 19 that, near the beam waist, a Gaussian TEM00 mode laser field acts much like a plane wave of truncated transverse dimension. At the point of refraction out of the first prism, the angle of incidence is equal to the apex angle u of the prisms. To negate the diffraction effects, one can enlarge the aperture so that D 4.5w. Now the second object distance, in general, is given by s2 = t - s1œ (25) 36 Chapter 2 Geometrical Optics where t is the thickness of the lens. Accordingly, the degree of convergence V¿ of the image rays is determined by the original degree of convergence V of the object rays and the refracting power P of the lens, that is, the power to change incident wave curvature. The screen may be the retina or a photographic plate. A schematic of the LIGO instruments being constructed and an aerial view of one of the installation sites are shown in Figure 17. Difficulties in the wave theory seemed to show up in situations that involved the interaction of light with matter. Practically, this means that every other Fresnel zone in the wavefront should be blocked. When the TA of 350 351 Production of Polarized Light y x TA Unpolarized light TA Polarizer TA TA Figure 1 Crossed dichroic polarizers functioning as a polarizer-analyzer pair. We assume that the surface integral over a closed surface including the aperture is zero everywhere except over the aperture itself, so that we need perform the integration only over the aperture in the yz-plane of Figure 11a. Gas atomic lasers typically emit laser light with frequencies in the visible to near-infrared range. The frequency range ¢ngain supported by the gain medium is ¢ngain = c c l1 l2 = 13 * 108 m>s2a 1 1 b 632.800 * 10-9 m 632.802 * 10-9 m = 1.50 * 109 Hz c. We can make some practical assumptions that will simplify Eqs. 1m 0.1 cm 0.2 0.5 0.8 1 cm 2 5 8 10 cm 20 50 Aperture diameter (D) 6 Anthony E. The Huygens-Fresnel principle does not include the contribution to the diffraction field of the electronic oscillators in the screen material at the edge of the aperture. Reflectance curves are shown in Figure 9. Employing L'Hôpital's rule for any m = 0, ;1, ;2, Á , sin Na N cos Na = lim = ;N cos a a : mp sin a a : mp lim Thus, the interference factor in Eq. (32) describes a series of sharp irradiance peaks (principal maxima). Many, therefore, leave through the sides of the laser cavity and are lost. If the photoemitted electrons are simply collected by a positive-biased anode in an evacuated tube, enabling a current to be drawn into an external circuit, the detector is called a diode phototube. (Here, l1 is the wavelength of the "short" wavelength end of the free spectral range.) Although the large order number of a typical Fabry-Perot interferometer is a disadvantage in that it leads to a small free spectral range, it is an advantage, as Table 1 indicates, in that it allows for higher resolving powers and smaller minimum resolvable wavelength separations. The real and imaginary parts of q(0) are two of the parameters that distinguish Gaussian beams one from another. Determine where the light is focused for light incident on each side. 9.99 × 105 ; 1570; 3.14 × 108 ; 8.4 × 10−8 ; 3.14 × 108; 1.6 × 10−6 nm; 250 nm; 0.16 nm; 3 GHz; 1.91 MHz 21. The first aperture is the AS of the system and, as we have seen, is related to an entrance pupil, its image in L1, and an exit pupil, its image in L2. A camera with a 4-cm focal length lens and stopped down to f/8 is used to photograph the object when it is placed 1 m from the lens. Apertures may also be used to shield the image from 50 Optical Instrumentation undesirable light scattered from optical components. (5) and (6) will destructively interfere if the difference in their phase constants is an odd multiple of p, that is, if a2 - a1 = 12m + 12p, where m is an integer. The minimum spot size w0 occurs at the so-called beam waist, where the wavefronts are planar. In this case, the amplitude of the 117 Superposition of Waves Thus a resultant wave is intermediate in magnitude between the magnitude of the sum and that of the difference of the amplitudes of the waves being superposed. To understand why this is so, note that k = 12p>l2 e. Practically speaking, the hole separation is a much smaller fraction of the cavity diameter, allowing a simple expression for the path distance, s2 - s1 . Incident radiation increases the temperature of the pyroelectric material and hence changes the charge on the surface of the metal. This rate can be increased by focusing on the pumped to the film using a laser. 11 a. It should be stated at the outset that the Huygens-Fresnel principle we shall employ to calculate diffraction patterns is itself an approximation. E. Beginning with a description of a single thick lens in terms of its cardinal points, the discussion proceeds to an analysis of a train of optical elements by means of multiplication of 2 * 2 matrices representing the elementary refractions or reflections involved in the train. P. Ray A does not meet the conditions for total internal reflection, that is, it strikes the fiber surface at point C, D, E, A such that its angle of incidence w is less than the critical angle wc , or w 6 wc = sin-11n2>n12 (2) Ray B, on the other hand, which enters at a smaller angle with respect to the axis, strikes the fiber surface at F with is such that it is refracted parallel to the fiber surface. Of particular interest in the context of this chapter, however, is the fact that scattered radiation may also be polarized. Or, as in Figure 22b, a ray leaving the tip of the object, directed toward the right focal point F of a diverging lens, undergoing refraction at the lens and emerging parallel to the axis. 22 Find the angle at which a half-wave plate must be set to compensate for the rotation of a 1.15-mm levorotatory quartz plate using 546-nm wavelength light. The sign convention is the same as that used previously in this chapter. In the absence of an Ex-component, the phase wy may be set equal to zero for convenience. We can give a reasonably accurate, though qualitative, understanding of laser operation by studying Figures 15 and 16. (3) to (8), a summary of some basic relations that unify particles of matter and light. Conservation of energy of the interacting particles requires that Uvg = Uv: Uv9 , or vg = v : v9 (19) This result shows that the diffracted photon differs in frequency—however little—from the incident photon by the amount v9 , greater or less, depending on the direction of the acoustic wave. If the polarizations of the individual fields produced by the independent oscillators are randomly distributed, the light is said to be randomly polarized or simply unpolarized. Equation (43) states that the amplitudes of reflected beams for rays incident from either direction are the same in magnitude but differ by a p phase shift. The pressure-broadening contribution to the gain bandwidth is, of course, pressure and temperature dependent. Qualitatively, the coherence time of the source is the time interval over which departures from monochromaticity are small. In Figure 1, the carrier sources output the optic fiber is represented by a single, square pulse. With the help of Figure 12c, the nodal plane distances y and x may be determined as follows. These three elements are shown schematically in Figure 13: as a unit in Figure 13a and separately in Figure 13b, c, and d. Applied to Eq. (18), this condition is 0n1 0t2 0P = K1 + K2 + 0 0l t0 0 fv (39) fR (a) V R TCA LA (b) Figure 12 Chromatic aberration (exaggerated) for a thin lens, illustrating the effect on the focal length (a) and the lateral and longitudinal misses (b) for red (R) and violet (V) wavelengths. Combining Eqs. E E E0 cos vt E0 t T Figure 16 Problem 2. dy a 1 Act z u ky Wa V ; u Ideal Actual Detail Wa Wi The derivative easily describes the local curvature of the wavefront at P. The analysis of the preceding section on the phenomenon of beats serves as a useful starting point for a quantitative discussion of the phase and group velocities of a wave pulse. First ensure that the approximations of problem 5 are satisfied. The higher-frequency cosine factor, in the resultant above is the carrier wave to distinguish it from the lower-frequency envelope wave. 12. No. 21 (October 14, 1976): 550. Using the results of problem 4, determine the magnitude of the spherical wave aberration for the telescope. It is a fundamental property of wave the nature of light that beams of finite transverse extent must spread as they propagate. Thus these lines are used to define a continuously changing beam width. The total longitudinal spherical aberration, shor - spar , of a thin lens with focal length f and index n, where shor is the image distance for a ray at elevation h, spar is the paraxial image distance, and 0 sd (26) Figure 7 "Bending" of a single lens into various shapes having the same focal length. Angles of incidence and refraction at each prism face are shown relative to the normals constructed at the point of intersection of the light ray. The hole at S is not necessary if the source is a spatially coherent laser. 30 Chapter 2 Geometrical Optics The focal point F, located a focal length f from the vertex of the mirror, and shown in Figure 16a and b, serves as an important construction point in graphical ray-tracing techniques, which we discuss following Example 1. Let us first concentrate on the integrals contained within the curly brackets, which we shall refer to as I. The factor e1 introduced in Eq. (7) for this purpose appears naturally in the Kirchhoff derivation of the same expression. The first of the right members is the sum of the squares of the individual terms of the sum in the left members. This widening of the beam follows from a further examination of the irradiance profile given in Eq. (25), which indicates that, at a given z, the irradiance I1r, z2 of a transverse distance r from the center of the beam is related to the axial irradiance I0 by a factor of 1>e2 40.135, when the transverse distance r from the beam axis is equal to the spot size, that is, when r = w1z2. Detection of Optical and Infrared Radiation. Fresnel's Biprism Figure 9 shows Fresnel's biprism, which reflects light from a small source S in such a way that it appears to come from two coherent, virtual sources, S1 and S2. 106 Chapter 4 Wave Equations In free space, the velocity c is given by c = 1 1e0m0 (31) where the constants e0 and m0 are, respectively, the permittivity and permeability of vacuum. For example, if selenium (six outer-shell electrons) is doped into GaAs, it replaces As (five outer-shell electrons) in the lattice. Rayleigh's criterion for just-resolvable images—a somewhat arbitrary but useful criterion—requires that the angular separation of the centers of the image patterns be no less than the angular radius of the Airy disc, as in Figure 20. What is the near point (with the corrective lens) for this eye? The optical rotation of the polarized light can be understood as circular birefringence, the existence of different indices of refraction for left-circularly and right-circularly polarized light components. To derive the Cauchy dispersion equation, let us first expand the frequency factor in a binomial series. Writing v = 2pc>l and gathering constants A¿, B¿, and C¿ appropriately, we can express n2 = A¿ + B¿ C¿ + 4 + A 2 l l We may take the square root of each side and, since each higher-order term in the series expansion is less than A¿, use the binomial expansion again on the right member. Such light patterns are not easily explained by viewing light as a stream of particles traveling in straight lines. New York: Pergamon Press, 1971. From ¢2, determine the spot size and location of the beam waist. We see that m = 1 for the first dark minimum in the slit pattern is replaced by the number 1.22 in the case of the circular aperture. The factor [1sin b2> b]2 is that of Eq. (10) for single-slit diffraction. That is, for spherical waves the irradiance (which is proportional to the square of the electric field amplitude) is proportional to 1>r2 and so the electric field amplitude of a spherical wave is proportional to 1/r. Using these constants and the Cauchy relation approximated by two terms, calculate the refractive index of the D Fraunhofer line for each case. The points O and I are said to be conjugate points for the optical system. Generally speaking, both surfaces of the lens might be cylindrical. Plot the wavelength parameter M¿ versus x in the range 0.70 to 1.70 mm. The detail shows a frontal view of a portion of a wavefront. Wavefronts propagating away from (or toward) the beam waist have reduced radii of curvature with the minimum 591 Characteristics of Laser Beams radius of curvature occurring at z = z0 . The pattern of interference fringes provides information on the relative vibrational amplitude as a function of position on the surface. Many mathematical manipulations can be carried out more simply with exponential functions than with trigonometric functions. However, the saturation irradiance is a property of the gain media and cannot be manipulated. The electrodes of the cell have a separation of 1.5 cm. 13 Apply the reasoning used to calculate the finesse of a FabryPerot interferometer to the Michelson interferometer. Cathode Anode 388 Chapter 17 Optical Detectors and Displays Another means of amplification, used in the gas-filled photocell, allows the generation of additional electrons by ionization of the residual gas. It is this sharing of the electrons that forms the crystal bond. 12 White light is passed through a Fabry-Perot interferometer in the arrangement shown in Figure 19, where the detector is a spectroscope. (a) 33.3 cm, 2 × (b) 66.67 cm, 2 × (c) 37.7 cm, −0.316 × 24. Both conditions require anisotropic crystalline structures. 448 Chapter 20 Aberration Theory From the plane mirror to the external beam waist, form the system matrix. Carry out the indicated matrix multiplication. Note that we have ignored the transfer matrix for propagation through the mirror-lens combination. Since output Mirror 2 is partially transparent, a fraction of the photons incident on the mirror pass out through the mirror. This plane wavefront, which constitutes the new surface of constant phase, is perpendicular to the propagation vector k for the wave. The first limitation determines how much of the surface of a broad object can be seen by looking back through the optical system; the second determines how bright the image can be, that is, how much irradiance 1W>m22 reaches the image. High-resolution, holographically recorded gratings have been used—instead of more expensive conventional gratings—in optical spectrometers. 21 A plane plate of beryl is cut with the optic axis in the plane of the surfaces. Popular LEDs include the infrared GaAs device, with a peak output wavelength near 900 nm, and the visible SiC device, with peak output at 580 nm. The periodic variation in R, which is proportional to the film thickness, provides a practical way of monitoring film thicknesses in the course of a film deposition. Now as the number N of slit increases, the brightness of the principal maxima increase as N2. Whichever eye is open when the pencil remains lined up with the reference object is your dominant eye. Figure 15 Transmittance of a Fabry-Perot interferometer of fixed length d as a function of the variable frequency n of the input field. Military applications include the use of a memory bank of holograms of particular objects or targets constructed from aerial photographs. (b) In steady state, the gain coefficient g1n2 at these frequencies to the threshold value g1n2 th. In the next section we examine the import of Eq. (14) and interpret the meaning of the imaginary part of q(0), z0 call the confocal parameter or Rayleigh range. In Figure 3a, an arbitrary ray PQ from an axial object point P is refracted by a Figure 3 Refraction of a ray at a spherical surface. Example 1 Determine the result of the superposition of the following harmonic waves: E1 = 7 cos1p>3 - vt2, E2 = 12 sin1p>4 - vt2, and E3 = 20 cos1p>5 - vt2 Solution To make all phase angles consistent, first change the sine wave to a cosine wave: E2 = 12 cos1p>4 - p>2 - vt2. At high magnifications, apochromats are usually objectives with focal lengths in the range of 1.5 to 4 mm. S. The uniqueness of the PCM is that the phase conjugate replica is produced regardless of the shape of the incident wavefront, as long as the PCM has an aperture large enough to receive the entire wavefront. Therefore as the irradiance increases, the population inversion in the gain medium decreases. For the simple cavity considered here, S = R1R2 8 . Z = 870 Vm, B = 290 × 10−6 T 16. 2 Matrix Treatment of Polarization 347 Example 2 Consider the result of allowing left-circularly polarized light to pass through an eighth-wave plate. Neither our first-order (Gaussian or paraxial) approximations nor third-order theory described in the preceding sections took into account an important fact of refraction: the variation of refractive index with wavelength, or the phenomenon of dispersion. If P is 30 cm away, as in the previous example, the radius of this aperture, by Eq. (20), is only 1.74 mm for 632.8-nm light. Such waves, which are of course also solutions to 103 Wave Equations Eq. (25), can be represented by the complex waveform. Here, r is the radial distance from the point source to a given point on the waveform, and for plane waves, k = 2p>l and v = 2pn. Calculate the radius of curvature of the grinding and polishing tools to be used in making this lens. Further, the conception of Figure 12 implies that the image size is identical with the object size, giving a magnification of unity. A perpendicular of height h is drawn from Q to the axis at Q. Thus, both the velocity and index of refraction of the extraordinary ray are continuous functions of direction. 410 Chapter 18 Matrix Methods in Paraxial Optics TABLE 2 CARDINAL POINT LOCATIONS IN TERMS OF SYSTEM MATRIX ELEMENTS Located relative to input (1) and output (2) reference planes Located relative to principal planes H1 H2 N1 N2 F1 F2 and r, are listed in Table 2. Since the film is air, nf = 1 and m = n2>2. The magnification of the microscope may then be expressed, perhaps more conveniently, as M = a 25 L b b fe (46) In many microscopes, the length L is standardized at 16 cm. Sensitivity (%) R = 100 60 40 20 0 4000 6000 8000 10,000 Wavelength (Å) Figure 7 Scaled responsivity as a function of wavelength for a CdS photoconducting cell. Irradiance variation in transverse plane Figure 2 Gaussian spherical beam propagating in the z-direction. When these minima happen to coincide with interference fringe maxima, the fringe is missing from the pattern. The minimum resolvable difference, dmin , between the cavity length associated with the centers of the peaks of the transmittance functions of the two wavelength components is equal to the FWHM of these peaks. One part is the fraction of the incident field that is transmitted through Mirror 1 at this time. In a simple model of diatomic hydrogen H2 , the resonant vibration frequency can be taken as f = 1.3 * 1014 Hz. a. Thus find the general matrix elements A, B, C, and D for a thick lens. If all spots are blocked except the DC component, or undeviated diffraction beam—say by an iris diaphragm centered on the central spot—the image plane is illuminated with no image present. What half-wave voltage is required? Equation (47) implies that for a two-mirror linear cavity. Similarly, the threshold gain coefficient is given. Mirror reflectances R1 = 0.99 and R2 = 0.98 that can be used in a He-Ne laser system given a small-signal gain coefficient of 0.001/cm. In Figure 11, the first-order spectrum spread (200 to 1200 nm) around the Rowland circle is shown for u = 38° and a grating of 1200 grooves/mm. The packaged diode is about 6 mm in diameter. When these few zones are reproduced on a smaller scale, the obliquity factor is not very important. Figure 6 Antireflecting triple layers. = n sin u (47) The numerical aperture is an invariant in object space, due to Snell's law. If the propagation constant is complex, so must be the refractive index. If we identify the real and imaginary parts of the complex refractive index as (31) where nR is the usual refractive index and nI is called the extinction coefficient, it follows from Eqs. The polarizer, preventing it from continuing back into the optical system, where, in high-power laser systems, it can damage optical components. Note that this relation gives the transmittance of a parallel plate. Estimate the small-signal gain coefficient for the Nd:YAG crystal. The material in this case is uniaxial negative, like calcite. (b) With this correction, can the myopic person also read a book held at the normal near point, 25 cm from the eye? Note that the amplitude of this field is, in general, time dependent to allow for the buildup or decay of the intracavity field as the incident field is turned on or off. Then the zone radii required to make the zones half-period zones relative to a fixed point P can be calculated. Probably the first measurement of the wavelength of light was made by Newton, using this technique. But since the cavity loss is high, the small-signal gain coefficient is less than the threshold value. That is, the irradiance of the reflected beam is 17% of the irradiance of the incident beam. The lateral magnification is defined as the ratio of lateral image size to corresponding lateral object size. Extending the sign convention to include magnification, we assign a 1+ 2 magnification to the case where the image has the same orientation as the object and a 1- 2 magnification when the image is inverted relative to the object. 23 The output from a single-mode TEM00 Ar laser has a far-field divergence angle of 0.001 rad and an output power of 5 W. Chapter 17 Without the use of a compensator, white-light fringes can be obtained only if the optical path lengths for each beam are the same (Figure 5). Find the irradiance entering the gain cell with the irradiance I0 input to the cell is (a) 1 W>cm2, (b) 10 W>cm2, (c) 100 W>cm2, (d) 1000 W>cm2, and (e) 10,000 W>cm2. 10 Suppose that the blue component of a white-light hologram is formed as in Figure 5, using light of a 450-nm wavelength. On the other hand, Figure 2b shows clearly that wavelengths within an order are better separated as their order increases. Figure 10 Gain saturation in a homogeneously broadened laser. The chief ray, together with its two marginal rays, is drawn from the tip of the object. In summary, we have shown that the amplitude E0 of the resultant field is given by Eq. (9) and the phase a of the resultant field is given by Eq. (10). Let the wire be aperture A and the slit be aperture B. The reflection and transmission amplitude coefficients are r and t at an interior reflection and r¿ and t¿ at an exterior reflection. How far away will the lights appear to be if they are just resolvable to a person whose nocturnal pupils are just 5 mm in diameter? This deficiency can be remedied to a degree by stepwise intensification of the reflected beam as in a pile-of-plates polarizer (Figure 5). New York: McGraw-Hill Book Company, 1968. Let the Fabry-Perot cavity have length d = 5 cm and finesse F = 30. The index of the glass is 1.50. 15 A camera is used to photograph three rows of students at a distance 6 m away, focusing on the middle row. The laterally scattered light of frequency less than v is known as the Stokes field, and that component with frequency greater than v is known as the anti-Stokes field. Charged particles, in turn, are accelerated by electromagnetic fields. Figure 6 Refraction by a spherical interface. Note that a plane surface can be treated as a special case of a cylindrical or a spherical surface in the limit that the radius of curvature R of either type of surface tends to infinity. For example, two lenses (of respective indices of refraction n1 and n2 and respective focal lengths f1 and f2) will have a flat Petzval surface, eliminating curvature of field, if n1f1 + n2f2 = 0. Optically, the eyeball can be pictured as a positive lens system that refracts incident light onto its inner curved surface to form a real image, much as does an ordinary camera. left member add to give the reciprocal of the focal length and (2) the reciprocals of the object and image distances describe the curvature of the wavefronts incident at the lens and centered at the object and image positions O and I, respectively. 156 Chapter 6 Properties of Lasers It is important to note that the angular spread increases as the beam waist is made smaller. That is, for solutions, r has units of degrees/dm # cm3/g. We close this chapter on geometrical optics with a brief look at this special type of lens. A measure of this capability is the product of half-angle and refractive index, called the numerical aperture N. Do this by plotting the longitudinal ray aberration as a function of ray height for h = 0, 1, 2, 3, 4, and 5 cm. The plots correspond to the different small-signal gain coefficients g0 and saturation irradiances IS indicated. This is a virtual image that serves as the object for lens L2 , with 1 s2 = 6 cm + 4 cm = 10 cm and f2 = - 10 cm. The largest telescopes, like the Hale 200-in. Similar interferometers are being developed by scientists and engineers in Europe and Japan. r 2 0.9 r 2 0.9 Transparent slab l 546 nm n 4.5 5 A Michelson interferometer is used to measure the refractive index of a gas. Thus r = y = a feq fB bL and s = w = -a feq fA bL (33) Example 4 Let us apply these results to the case of a Huygens eyepiece, which consists of two positive, thin lenses separated by a distance L equal to the average of their focal lengths. Notice that the two types of devices have figures of merit of similar form. In the same time interval, how far from the soprano has the sound wave in the auditorium traveled? Let us assume for the moment an ideal situation in which none of the energy is lost on reflection nor absorbed by the transmitting medium. The scattered light has a frequency that differs from that of the incident light by an amount equal to the frequency of the acoustic waves in the medium. • Ray 3. 19 Two thin lenses have focal lengths of - 5 and + 20 cm. If the terminal point B lies below the surface of a second medium, as in Figure 6, the correct path is definitely not the shortest path or straight line AB, for that would make the angle of refraction equal to the angle of incidence, in violation of the empirically established law of refraction. Let input parameters include thickness and indices of the layers and the index of the substrate. The photograph in Figure 16 allows one to appreciate the difference in scale between diode lasers and conventional table-top laser systems. 28.1% 67.5°; 22.5° (a) I0 {0.5(2 + 2) cos2 + sin2 } (b) 0.4525I0 versus 0.5I0 ; 0.351I0 versus 0.375I0; both 0.25I0; 0.0475I0 versus 0 0.0633 mm (a) single refraction, phase retardation, any polarization possible (b) single refraction, no phase retardation, unpolarized (c) same as (a) (d) double refraction, no phase retardation in each separated beam, each beam linearly polarized (e) cases (a) and (c) (a) difference of 0.121 mm (b) 0.015 mm (b) 0% (c) 33% 24 0.0162 mm 20° 0.005 (a) 53.12º (b) 11.5º (a) mixture of unpolarized and circularly polarized light (b) elliptically polarized light (a) 56.2º (b) 33.8º (a) 0.05 g/ml (b) 46º (a) 0.200 mm (b) 50º (b) green (a) 8.57 × 10−5 cm (a) 0.0091 (b) 15 μm (c) 12 (d) 15 μm 3.15 × 10−4 (a) 36.8 μm (b) 18.4 μm 14.7° (a) 14.8% (b) 2.03% of I0 (c) 0.92 I0 sin2(2) (a) 42.5° (b) 0.60° Chapter 16 2. For generality, we assume different media on opposite sides of the lens, having refractive indices n and n¿, as shown in Figure 8. PROBLEMS 1 When one mirror of a Michelson interferometer is translated by 0.0114 cm, 523 fringes are observed to pass the crosshairs of the viewing telescope. The tungsten lamp is an extended source that emits many wavelengths. In addition, the output power can be very high. The technique of shaping individual grooves so that the diffraction envelope maximum shifts into another order is called blazing the grating. Holocameras A device called a holocamera does not use photographic film, but rather materials like thermoplastics to record a holographic image. One can show that coma is absent in a lens when s = a 2n2 - n - 1 s - s¿ ba b n + 1 s + s¿ (31) For the example of the lens considered previously, with n = 1.50 and object at infinity, Eq. (31) gives a value of s = 0.8, quite close to the value of s = 0.7, which yielded minimum spherical aberration. (a) 3.6 cm−1 (b) 2450 (c) 0.093 mm/s Chapter 22 2. The image occupies essentially the region of the Airy disc. Infrared Radiation On the long-wavelength side of the visible spectrum, infrared (IR) radiation has wavelengths spanning the region from 770 nm to 1 mm. The Bunpolarized light incident from the left (along the x-direction) contains E-field components oscillating along the y- and zB directions. 8 REFRACTION AT A SPHERICAL SURFACE We turn now to a similar treatment of refraction at a spherical surface, choosing in this case the concave surface of Figure 18. 14 What acoustic frequency is required of a plane acoustic wave, launched in an acousto-optic crystal, so that a He-Ne laser beam is deflected by 1°? Interference techniques are not practical in the production of coarse, echellelike gratings. When Eq. (30) is rearranged to express the lateral magnification, the condition can be written m = n sin u h¿ = h n¿ sin u¿ To prevent coma, the lateral magnification resulting from refraction by all zones of a lens must be the same. Explain why, for this system in which there are unavoidable losses, the output irradiance is reduced from its maximum value if T3 is either too large or too small. (b) Virtual image, concave mirror. (a) l>4 – l>4: n1 = 1.38, n2 = 2.02, n3 = 1.8. (b) l>4 – l>2 – l>4: n1 = 1.38, n2 = 2.2, n3 = 1.7. (b) 1 350 450 550 650 Wavelength (nm) 750 850 487 Theory of Multilayer Films We derive now an expression for the reflectance of this type of structure, shown schematically in Figure 8, where High and Low signify highand low-refractive indices, respectively. m 3 m 5 1 2 2 m 2 m 3 1 2 2 m 1 m I 1 1 2 2 m 0, y 0 m 1 1 2 2 m 1 m 3 1 2 2 m 2 m 5 1 2 2 m 3 Figure 4 Irradiance versus distance from the optical axis for a double-slit fringe pattern. Figure 10 Transmittance T as a function of round-trip phase shift d. A schematic of an optical communications system employing WDM is shown in Figure 15. As time progresses, the tip of the electric field vector traces out positions along the extent of the double-headed arrow. 14 A high-reflectance stack of alternating high-low index layers is produced to operate at 2 mm in the near infrared. This light is used to form fringes in an interference experiment in which the light is first amplitude-split into two equal parts and then brought together again. (37) and (44), the powers of the individual elements may be expressed in terms of the desired power PD of the combination: P1D = PD - V1 V2 - V1 and P2D = PD V2 V2 - V1 (45) The K curvature factors expressed in Eqs. The relationships listed there can be used to establish the following useful generalizations: fA fB 10 EXAMPLES USING THE SYSTEM MATRIX AND CARDINAL POINTS L RP1 1. Example 1 and Figure 7 illustrate the formation of fringes in a holographic grating by the interference of two argon-ion laser beams. For example, consider an electric field propagating in the positive zdirection and polarized in the x-direction, B E = E0 sin1kz - vt2xN (43) According to Maxwell's equations, the magnetic field associated with this electric field would be 1 B B = a b E0 sin1kz - vt2yN c and Eq. (40) would give the Poynting vector as S = e0cE20 sin21kz - vt2zN B The polarization of an electromagnetic wave determines the direction of the force that the electromagnetic wave exerts on charged particles in the path of the wave through application of the Lorentz force law. 353 Production of Polarized Light 2 POLARIZATION BY REFLECTION FROM DIELECTRIC SURFACES Light that is specularly reflected from dielectric surfaces is at least partially polarized. Within months of the arrival of Maiman's ruby laser, which emitted deep red light at a wavelength of 694.3 nm, A. The Nature of Light. This field of view can be described in terms of the lateral dimensions of the object viewed, or in terms of the angular extent of the window, relative to the line of sight. In this section we will describe several basic types of thermal detectors. Using Eq. (43), Q = n 5 * 1014 Hz = = 5 * 106 2¢n1>2 108 Hz d. Assume a thin lens. 126 Chapter 5 Superposition of Waves Thus, the interaction with the medium that results in absorption generally also affects the speed of the wave. A brief description of spherical and chromatic aberration will serve us here as a useful background for the treatment of optical elements and instruments that conclude this chapter. First, a pinhole can be used with the light source to limit the spatial extent of the source. Example 4 Consider a Mach-Zehnder interferometer of the type just described and illustrated in Figure 16b. Fraunhofer's original gratings were, in fact, fine wires wound between closely spaced threads of two parallel screws or parallel lines ruled on smoked glass. The beam is focused to a beam waist w02 a distance Z2 away. Since the length of the slit is very large compared to its width, the diffraction pattern due to points of the wavefront along the length of the slit has a very small angular width and is not prominent on the screen. The coherence length can also be expressed as p p p = ¢k 2v 4p ¢n ¢n c l0 l0 LC = 4 ¢n LC = where we have used k = nv c and ¢k = (6) n2v12v2 2nv1v2 2v = ¢n c c c In Eq. (6), l0 is the vacuum wavelength of the fundamental and ¢n the amount the index of refraction of the fundamental differs from that of the second harmonic. (b) 2 in. Thus, l = 2p 2 v = m and n = = 5 Hz k 3 2p The initial phase 1x = 0, t = 02 is p>4. Those along the y-direction are absent beB cause they would represent longitudinal E-vibrations in an electromagnetic wave. c 2d d Mirror Mirror c 2l Laser tube Etalon l Frequency (a) (b) Figure 16 (a) Laser with intracavity etalon for single-mode operation. In the output plane where the detector is placed, we expect to measure the spectrum or Fourier transform of the transmission function represented by the light transmitted through the mask located in the image plane of Figure 7. Smith, F. 23. 23 The Fresnel equations show that the fraction r of the incident field that is reflected from a dielectric plane surface for the TE polarization mode has the form, Unpolarized light y TA y x FA u TA x Polarizer x Half-wave plate Analyzer Figure 26 2 a. The electric field associated with a plane monochromatic electromagnetic wave is perpendicular to the direction of the propagation of the energy carried by the wave. Since rays are reflected to any point P from the two film surfaces as if they originated at the virtual sources S1 and S2 , this may be considered an instance of the two-point source pattern already discussed in connection with Figure 6. When the normal eye looks at objects at the near point, diverging light enters the tensed 429 Optics of the Eye Myopic eye (unaided) Normal eye Blurred vision Distant object Myopic eye (corrected) Lens (negative power) Distinct vision Distant object Object at infinity F.P. M.F.P. No accommodation No accommodation (a) No accommodation (c) (f) Distinct vision M.F.P. No accommodation (d) Distinct vision 25 cm 25 cm Object at N.P. M.F.P. Full accommodation (b) M.F.P. N.N.P. M.N.P. N.N.P. M.N.P. Full accommodation (e) Figure 5 A comparison of normal and myopic vision, with optical correction. Fiber Optics 249 the boundary, a second medium introduced into this region can couple into the wave and provide a means of carrying away energy that otherwise would return into the first medium. Introduction to Matrix Methods in Optics. 23 Trace two rays, both from far-distant objects, through a Protor photographic lens, one at altitude of 1 mm and the other at 5 mm. Here also, image brightness is proportional to the square of the numerical aperture. Thus, Ee = £e 4pIe d£ e Ie = = = 2 , point source 2 dA A 4pr r (11) The radiance, Le , describes the radiant intensity per unit of projected area, perpendicular to the specified direction, and is given by Le = dIe d2 £ e = dA cos u dv1dA cos u2 (12) The importance of the radiance is suggested in the following considerations. (a) = 2 sin[2(z/5 m + t/3 s)] (b) = 2 sin(2/5)(z/m + 53 t/s) (c) = 2 exp[(2i(z/5 m + t/3 s)] 6. Relate the wavefront curvature at R2— where the wavefront curvature matches the mirror curvature—to the spot size w1 at the plane mirror and the distance z2 = d from plane to curved mirror R2 . (12) to (14), the cosine factors in the g-terms are all unity. If its theoretical resolving power in first order is to be 300,000, determine the proper blaze angle for use (a) in a Littrow mount and (b) with normal incidence. Draw the chief ray from object point P to its conjugate in the final image, P–. Thus the treatment in terms of meridional rays is a two-dimensional treatment,4 greatly simplifying the geometrical relationships required. Just when a lens moves from the category of thin to thick clearly depends on the accuracy required. This is equivalent to a comparison of coherence along any radial direction of light propagation from the source at two wavefronts separated by the same path difference. For example, ! consider the spiral points F and G shown in Figure 12. Find the pump irradiance Ip required to sustain a smallsignal gain coefficient of 1/cm. 238 Chapter 9 Coherence S1 u s P ls S2 r Figure 12 Lateral region of coherence ls , due to two independent point sources. That is, the pump energy stored in the gain medium is converted to irradiance by interaction of the electromagnetic field with the gain medium. What is the beat frequency of the photocurrent when the input is the yellow light of sodium, at 5889.95 Å, and 5895.92 Å? n1L 1n21 - sin2 u21>2 c. The regions ascribed to various types of waves, as shown, are not precisely bounded. Depending on the degree 5 Ivan P. for 20/15. (20) and (22) written in the form tTE = 1 + rTE ntTM = 1 - rTM into which the results expressed by Eqs. Laurance) that represents a living, biological eye with fair accuracy is shown in Figure 3. Such distortion is often augmented due to the limitation of ray bundles by stops or by elements effectively acting as stops. 285 286 Chapter 11 Fraunhofer Diffraction and EP = EL i1kr0 - vt2 b sin b sin Na e e f r0 b sin a As before, the irradiance is proportional to the square of the field amplitude, sin b 2 sin Na 2 b a b b sin a 5 5 diffraction interference I = I0 a (32) where I0 includes all the constants, the first set of brackets encloses the diffraction factor, and the second set of brackets encloses the interference factor. Assume an equilibrium length of 1 km and determine for this fiber length the 3-db bandwidth of a step-index multimode fiber whose pulse broadening is given by 20 ns/km. Concave mirror: f = + 10 cm and s = + 20 cm. Note B that the k-vectors representing the two pairs of counterpropagating waves comprising the degenerate four-wave mixing process satisfy the phase matching condition, B B B B B B B B k1 + k2 + k3 + k4 = k1 - k1 + k3 - k3 = 0 We have seen that the phase conjugate wave 1A 42 exactly reverses the direction and overall phase factor of the signal wave 1A 32. Radio Waves Radio waves are long-wavelength EM radiations produced, for example, by electrons oscillating in conductors that form antennas of various shapes. The pinhole-to-film distance, while not critical, does affect the sharpness of the image and the field of view. 1 1 : linearly polarized at −45° √2 [−1] 1 1 : √2 [1] linearly polarized at +45° 1 1 1 √2 [√2 (1 1 1 : √2 [i] − i)]: right-elliptically polarized at +45° left-circularly polarized (a) linearly polarized along x-direction, traveling in +z-direction with amplitude of 2E0 (b) linearly polarized at 53.1º relative to the x-axis, traveling in the +z-direction with amplitude of 5E0 (c) right-circularly polarized, traveling in –z-direction with amplitude of 5E0 75° right-circularly polarized light = E0 √3 + ei(kx−t) (a) (= E0 (2 − i)ei(ky−t) (b) = E0 exp i (x + y)k/√2 − t (c) {[ ]} 7. A slide that will be projected or a negative that will be enlarged requires better original detail and hence a sm value for d. The solar cell and the photographic exposure meter are two well-known applications of the photodiode operating in the photovoltaic mode. For example, consider a linear polarizer with a transmission axis along the vertical, as in Figure 8. Any small, remaining inequalities in optical paths can be removed by allowing the compensator to rotate, thus varying the optical path through the thickness of its glass plate. Thus, 28E1 # E29 = E01 # E028cos1b - a29 = E01 # E028cos1k1s2 - s12 + f2 - f129 B B B B B B K E01 # E028cos d9 B B (7) B B where we have defined the phase difference between E2 and E1 as d = k1s2 - s12 + f2 - f1 (8) For purely monochromatic fields, d is time-independent, in which case 8cos d9 = cos d. In this case, as D winds around the turns of part of the Cornu spiral, the irradiance at P¿ oscillates with various maxima and minima points, as shown in Figure 14c. Before examining spherical aberration in more detail, however, we wish to show how the other third-order aberrations arise. Thus, R can be found. (32) and (33). Highly reflecting mirror Wavefronts Output coupling mirror Beam divergence angle u Beam waist (radius w0) Laser cavity External laser beam l u pw0 Figure 19 External and internal laser beam for a given cavity. If, instead, both reflections are external 1n0 6 nf 6 ns2 or if both reflections are internal 1n0 7 nf 7 ns2, no relative phase difference due to reflection needs to be taken into account. The cones, sensitive to light signals of high intensity and variable color composition (photopic vision), each contain one of three different kinds of visual pigment. As the light propagates in the z-direction across the medium, there can be an exchange of energy between the light and the atoms in the medium. This direction of symmetry through the crystal is called the optic axis (OA) of the crystal. To produce faithfully the sinusoidal variation in the transmittance of the grating, what bias is required in the transmission function, assuming 100% maximum transmission? In practice, mirror M can be moved toward or away from the beam splitter to equalize optical-path lengths and can be tilted to make M¿ more or less parallel to the film surface. 18 Answer problem 17 when the lens is designed to reduce coma. Outside the central stopband—the region of highest reflectance—the TABLE 2 REFLECTANCE OF A HIGH-LOW QUARTER-WAVE STACK Reflectance for N ჳ 3 high-low layers versus nL>nH Reflectance versus N when nL>nH ჳ 0.587 for alternating double layers of MgF2 and ZnS nL>nH R (%) N R (%) 1.0 0.91 0.83 0.77 0.71 0.67 0.625 0.59 0.56 0.53 0.50 4.26 21.01 40.82 57.77 70.44 79.35 85.48 89.67 92.55 94.56 95.97 1 2 3 4 5 6 7 8 39.71 73.08 89.77 96.35 98.72 99.56 99.85 99.95 489 Theory of Multilayer Films 100 (b) 90 (c) 80 70 (a) R (%) 60 50 40 30 20 10 Uncoated glass 350 450 550 650 Wavelength (nm) 750 850 Figure 9 Spectral reflectance of a highlow index stack for (a) N = 2 and (b) N = 6 double layers. In the configuration of Figure 9a, light would be transmitted through the cell. As a result, only pulses timed to pass through the gate when it is open can survive in the cavity. As we have noted previously, this is known as dispersion. In Eq. (9), v and k refer to the properties of the incident and diffracted radiation. Use the Jones matrix technique to determine and describe the product light. What is the range of photon wavelengths that could ionize a hydrogen atom that is originally in its ground state? Calculate the separation of the dark fringes. In this model, the resultant image is considered to be the overlapping of such "blurred" image points. 607 608 References Reynolds, George O., John B. For closer objects, the focus falls beyond the film. The image is a sinusoidal pattern of the other frequency. The justification of this identification makes clear that it is only reasonable near the beam axis. 20 40 60 Angle of incidence (deg) 80 A d d/2 u u B d/2 u u Figure 11 Progress of a ray through a prism under the condition of minimum deviation. So, O–P–, as shown in the final drawing, is real, inverted, 3 cm long (same as the object), and 10 cm from L2 . We note that it Figure 7 Sequence of harmonic wave trains of varying finite lengths or lifetimes t. In fact, if the dipoles radiated along the reflected ray, the electromagnetic wave could only be a longitudinal wave! This unique orientation results Es (a) Ep (b) up up n1 n2 ut (c) Figure 4 Specular reflection of light at a dielectric surface. For the case consideredBin Figure 1, E is everywhere tangent to the planes at (a) and (b), whereas B consists of both a tangential component (ydirection) and a perpendicular component (x-direction). We know of no simpler physical model that is adequate to handle all cases. The absence of the even harmonics might at first be puzzling, on the basis of Eq. (23), since it would lead us to expect all the higher harmonics in the representation. The gate opens for a brief time during each round-trip to let the pulse pass. One of these phosphors in a cluster emits blue light, one emits red light, and one emits green light when struck by an electron beam. How much information could be stored in the 1-mm-thick CD if the data could be stored holographically throughout the entire CD at the same information density? The result (see problem 3) is N2 = NT a sI>1hn¿A 212 b 1 + 2sI>1hn¿A 212 (17) N1 = NT a 1 + sI>1hn¿A 212 b 1 + 2sI>1hn¿A 212 (18) We shall see that the population inversion Ninv K N2 - N1 is of physical interest. The distance from pinhole to slits is 1 m. y x Unpolarized light 45 TA TA LP FA SA QWP Figure 11 Production of right circularly polarized light. Assuming n = 1.50 for the glass lens, ideally nf = 21.50 = 1.22. The "miss" along the optical axis, represented by the distance LI, is called the longitudinal aberration, and the miss IS, measured in the image plane, is called the transverse, or lateral, aberration. This integral has other important applications in physics. As P¿ moves up the screen, D moves down along the spiral shown in Figure 14b. (10) and (11) we used the fact that the time average of the square of a rapidly oscillating sinusoidal function is 1/2. Direct light from the sun has a spectral distribution that is clearly different from that of skylight, which has a predominantly blue hue. In Eq. (34), the reflection coefficient takes the form rTE = 1a - ib2>1a + ib2. The change in speed modifies the rate of energy propagation and thus the power of the beam; the change in direction modifies the cross section and thus the power density of the beam. Liquid-Dye Lasers The gain media in liquid-dye lasers are solutions of certain long-chain organic molecules in alcohol or other solvents. The condition for constructive interference at a point P on the screen is, then, to a very good approximation s2 - s1 = ¢ = ml a sin u (19) whereas for destructive interference, ¢ = A m + 12 B l a sin u (20) where m is zero or of integral value. The lenses have focal lengths of fA and fB , which may be either positive or negative. This is an important general feature of the propagation of electromagnetic waves. The curve for the case of external reflection, TM mode, indicates that no wave energy is reflected when the angle of incidence is near 60°. We have looked in detail at the behavior as p ranges from 0 to N. In Figure 8c, where the mirror does not lie directly below the object, the mirror plane may be extended to determine the position of the image as seen by an eye positioned to receive reflected rays originating at the object. 8 Quarter-wave thin films of ZnS 1n = 2.22 and MgF2 1n = 1.352 are deposited in turn on a substrate of silicon 1n = 3.32 to produce minimum reflectance at 2 mm. Here, I1 and I2 are the irradiances due to the reference and signal beams, respectively, s is the distance of the object point from the film, and l is the wavelength of the light. We shall neglect lens aberrations and 462 Chapter 21 Fourier Optics Y y X x m2 m1 m0 z m 1 m 2 L1 L2 Aperture plane Figure 2 Fraunhofer diffraction of a Ronchi ruling. Following this we note the errors of refraction in a defective eye and indicate the usual corrective optics. Just as for a prism, greater refraction of shorter wavelengths brings the violet focus nearer the lens for the positive lens shown. The image distance s¿ is positive when I is to the left of V, corresponding to a real image, and negative when I is to the right of V, corresponding to a virtual image. If the TAs of the filters are crossed, no light emerges from the pair. Sliney, D. The offset detail construction of Figure 2 then shows that the incremental wave aberration da, expressed as an optical path length in image space, is da = n21a dy2 (1) W1 W2 A B Ide Ac tua al r lr Optical system O ay ay L I S Actual wavefront Ideal wavefront Paraxial image plane Figure 1 Illustration of ray and wave aberrations. Absorption losses over a length L of fiber can be described by the usual exponential law for light irradiance I, I = I0e -aL (12) where a is an attenuation or absorption coefficient for the fiber, a function of wavelength.5 For optical fibers, the defining equation for the absorption coefficient in decibels per kilometer (db/km) is given by adb K 110 db>km2log10 a P1 b P2 (13) where P1 and P2 refer to power levels of the light at two fiber cross sections separated by 1 km, as illustrated in Figure 7. This scattered light can include only E-field components polarized along the direction of the forced motion executed by the oscillators, that is, 2 The more general theory of scattering, including larger scattering centers, is often called Mie scattering after its creator. Davis, Lasers and Electro-Optics (Cambridge, UK: Cambridge University Press, 1996), Ch. 22. The aperture might be the input aperture of a detecting instrument measuring all the flux that so enters. The two cones–defined by the pairs of rays a, a¿ and b, b¿ –emerging from the points O and O¿ are limited by the size of the entrance pupil A 1œ and just make it through the exit pupil A 2œ . (a) y = (5 m) sin(x/25 m) (b) y = (5 m) sin[(/25)(x/m + 8)] 7. Since these rays differ very little in direction, they will appear to originate from approximately the same image point. The crests and valleys of spherical waves from S1 and S2 are shown approaching the screen. It is important to note that there is also a maximum wavelength separation, ¢lmax, that can be resolved in an unambiguous manner. Solution Here, l = 513 nm and l¿ = 525 nm. Since E has a sinusoidally varying magnitude as it progresses, the electric field vector varies between, say, AyN and - AyN . The high coherence of laser light allows the beam to be focused onto 1 We speak here of the electric polarization, rather than wave polarization. 14 A small goldfish is viewed through a spherical glass fishbowl 30 cm in diameter. Note that the bands are curved and contain states of differing energy E since the carriers in the bands can have different momenta pc . Since p r¿, the condition for significant curvature (near-field case) is (b) ¢ h2 h2 7 l 2r¿ 2p (9) Figure 2 Edge view of Figure 1. When all waves arrive in phase, the resulting phasor diagram is formed by adding N phasors all in the same "direction," giving a maximum resultant. The laser frequency could be changed, for example by changing the effective length of the laser cavity. The mixing of spontaneous emission into the laser output and environmental noise fluctuations prevent laser light sources from emitting perfectly coherent light. It is useful to note that C1y2 and S1y2 are both odd functions so that C1- y2 = - C1y2 S1 - y2 = - S1y2 Table 1 provides numerical values of these definite integrals for various values of y. Estimate the electric field amplitude and irradiance that would cause the second-order nonlinear contribution to the polarization to be 1% of the linear contribution in KDP 1KH2PO42. When the slit separation a reaches a value of 0.1 mm, ƒ g ƒ = 0 and the fringes disappear. First, the fringes show poor contrast, because the two transmitted beams with largest amplitudes have quite different values and result in incomplete cancellation. Operating in the green at about 550 nm, what is the resolving power in the third order? (55) and (56) and equating their real and imaginary parts, the optical constants nR and nI can be 507 Fresnel Equations found in terms of the conductivity by the equations n2R - n2I = 1 s 2nRnI = e0v (57) Furthermore, if the complex character of k in the form ' v ' v k = a b n = a b[nR + inI] c c (58) is introduced into the harmonic wave, Eq. (52), the result is E = E0e -1vnIs>c2eiv1nRs>c - t2 (59) where s is the directed distance along the propagation direction. 3 SPOT SIZE AND RADIUS OF CURVATURE OF A GAUSSIAN BEAM Motivated more by hindsight than by foresight, we write q(z) in the form2 1 1 l = + i q1z2 R1z2 pw1z22 (17) Here, R(z) and w(z) are real functions. The speed of light in a linear nonmagnetic material can be written as y = 1> 1em0 and the index of refraction of such a material is n = c>y = 1em0> 1e0m0 = 1e>e0. 3 THE TRANSLATION MATRIX y1 Optical axis Simple translation of a ray. There are, however, several important differences between the underlying systems and their behaviors. For m = 10.2 mm2 For m = 10.2 mm2 E0 EDC ky (b) E EDC E0 sin ky Figure 4 Sinusoidal amplitude or transmission functions including negative displacements. In a photodiode such a p-n junction is established between electrical contacts, as shown in Figure 4. To define this quantity precisely, we utilize Figure 22, which shows an axial object point O at distance s0 from a lens being imaged at O¿, a distance s0œ on the other side. Using Euler's theorem on the integrand, we may write EP = Apei1kD - vt2 e y2 Ly1 cos a y2 py2 py2 b dy + i sin a b dy f 2 2 Ly1 (29) The two integrals in this form can be expressed in terms of the Fresnel integrals, which we name y C1y2 K 3 0 cos a py2 b dy 2 (30) 322 Chapter 13 Fresnel Diffraction y S1y2 K 3 sin a py2 b dy 2 (31) 0 Using these, Eq. (29) may be written as EP = Apei1kD - vt21C1y22 - C1y122 + i1S1y22 - S1y122 Now the irradiance at P, since Ip = IP = (32) 1 e c ƒ EP ƒ 2, is given by 2 0 1 e c ƒ Ap ƒ 251C1y22 - C1y1222 2 0 + 1S1y22 - S1y12226 K I051C1y22 - C1y1222 + 1S1y22 - S1y12226 (33) Here we have defined the irradiance scale factor I0 = 11>22e0c ƒ Ap ƒ 2. The situation is much the same as when looking through a small, square aperture placed in front of a window. 476 477 Theory of Multilayer Films The relationships we require from electromagnetic theory are summarized here. Chapter 11 Ball, C. The ultimate goal of optical design is to reduce the ray aberrations until they are comparable to the unavoidable blurring due to diffraction itself. An optical cavity that confines and directs the growing number of resonant energy photons back and forth through the laser medium, continually exploiting the population inversion to create more and more stimulated emission, thereby creating more and more photons directed back and forth between the mirrors. 7. They apply also to a medium of refractive index n if e0 is replaced by n2e0 and c is replaced by the velocity c/n. This decrease in population density, of course, is accompanied by a rapid increase in photon number density. (6) and (7) can be used in this relation to give 8phn30 c 3 1 e hn0>kBT = B12e - 1 A 21 hn0>kBT - B21 Rearranging to isolate multipliers of the term ehn0>kBT, a 8phn30 B12 hn0>kBT 8phn30 A 21 A 21 b e a b = 0 B21 B21 c3 B21 c3 In order for this relation to be true at all temperatures T, the term that multiplies ehn0>kBT and the remaining term in parentheses must each be identically zero. The amount of light at the image position is determined by the amount of light from the source intercepted by the lens. At such points, the principal maxima of Figure 15 are produced. I = I0 (2 sin2 cos2) 1. As a point of reference for judging the departure of defective vision from the norm, refer to the normal eye depicted in the left column of Figure 5. From then on, light was viewed as a particular region of the electromagnetic spectrum of radiation. Introduction to Classical and Modern Optics, 3d ed. 255 Fiber Optics with only one propagating mode. More precisely, a1Q2 = 1n1/ + n2/¿2 - 1n1s + n2s¿2 (6) Employing the cosine law in triangles PQC and CQI, the lengths / and /¿ may be exactly expressed, in terms of the quantities defined in Figure 3, by /2 = R2 + 1s + R22 - 2R1s + R2cos f (7) /¿ 2 = R2 + 1s¿ - R22 + 2R1s¿ - R2cos f (8) cos f = 11 - sin2 f21>2 = [1 - 1h>R22]1>2 (9) Now, where we have used the fact that sin f = h>R. After integration and substitution of limits, we get K = 1 5e -ik sin u[12j - 12a - b]>2 - e -ik sin u[12j - 12a + b]>26 ik sin u + 1 5eik sin u[12j - 12a + b]>2 - eik sin u[12j - 12a - b]>26 ik sin u Using Eqs. The pump can be an optical, electrical, chemical, or thermal energy source. The spacing, or thickness, d of the air layer, is an important performance parameter of the interferometer, as we shall see. 14.9 cm 27. This nonlinear phenomenon is discussed in the next section. The carbon (C) and oxygen (O) atoms form the base of the pyramid, as shown, with carbon lying in the center of the equilateral triangle of oxygen atoms. In the analysis leading to the irradiance that results from the superposition of two mutually coherent beams, Eq. (14), we assumed that the individual beams were plane waves described by Eqs. The frequency of a photon with this energy is E2 - E1 = hn0 Q n0 = E2 - E1 1.63 * 10-18 J = = 2.46 * 1015 Hz h 6.63 * 10-34 J # s The wavelength of this photon is l0 = 3 * 108 m>s c = = 1.22 * 10-7 m = 122 nm n0 2.46 * 1015 Hz Lineshape Function We have, so far, treated the energy levels of atoms as if they were truly discrete. 12 For each case of problem 11, find the irradiance added by passage through the gain cell IL - I0 and describe how this added irradiance changes with increasing input irradiance. Consequently, when a Polaroid H-sheet is crossed with another such sheet acting as an analyzer, the combination contributes a blue tint to the almost canceled transmitted light. (a) 750 MHz (b) 750 MHz (c) 154 MHz (d) 154 MHz (e) 308 MHz 2 2 2 This is achieved by the pumping process and the existence of a metastable upper laser state. Thus the condition for the principal maxima is simply a = mp m = 0, ;1, ; 2 Á Recall from Eq. (25) that a = 11>22ka sin u = pa sin u>l, so that the condition for the existence of a principal maximum can be recast as ml = a sin u sin2 b sin21Na2 (34) 288 Chapter 11 Fraunhofer Diffraction Equation (34) is sometimes called the diffraction grating equation and m is identified as the order of the diffraction. In that case, constructive interference occurs at P. Sketch the arrangement, showing the OA of the crystal, and explain why this occurs. Thus a detector, placed on axis at the output plane in the optical correlation system of Figure 7, measures the correlation. Figure 6b illustrates the effect of spherical aberration in a thin-lens system that forms a blurred line image of an axial point object. (a) 0.5 μm (b) 2 × 10−8 μm (c) −2.48 × 10−6 μm 22. Since dy = fdu, the linear dispersion is given by linear dispersion K dy dum = f = fD dl dl (6) The reciprocal of the linear dispersion is known as the plate factor. Thompson. 13 Plot the spectral exitance Ml for a graybody of emissivity 0.4 in thermal equilibrium at 451°F, the temperature at which paper burns. r11 = 8.5168 cm; r22 = −434.89 cm; fD = 20.0000 cm, fC = 20.0096 cm; fF = 20.0096 cm 22. An object 5 cm high is placed 60 cm in front of the lens surface. White, Fundamentals of Optics, 4th ed. The speed of sound in the crystal is 2500 m/s and its refractive index at 632.8 nm is 1.6. 15 In Bragg's equation (18), the wavelength of the light and the angle are those measured within the medium. The edges of the window determine how much of the outdoors we can see. 22 A quarter-wave plate is placed between crossed polarizers such that the angle between the polarizer TA of the first polarizer and the QWP fast axis is u. When the refracting medium has characteristic excitations that absorb light of wavelengths within the range of the dispersion curve, the curve is monotonically decreasing, as shown, but has a positive slope in the wavelength region of the absorption. Note that the propagation constant k is related to the spatial period (i.e., the wavelength) of the wave in the same way that the angular frequency v is related to the temporal period T. of radiant flux would produce only 0.5 * 685 or 342 lm of luminous flux. With the lens of part (a), what is the far point of the corrected eye? Intentional limitation of the field of view using an aperture is desirable when either far-off axis imaging is of unacceptable quality due to aberrations or when vignetting severely reduces the illumination in the outer portions of the image. Reflection from the bottom surface; 1.60 1.55 1.153 cm 8 cm Light from the bubble is refracted through the plane surface, both directly and after reflection from the spherical mirror; 3.33 cm and 10 cm. It is convenient to choose the z = 0 plane to be the plane in which q(z) is purely imaginary. However, Fresnel and Arago showed experimentally that the spot, now known somewhat ironically as Poisson's spot, did occur as predicted. By doing so the dwell time of the atoms in the upper lasing level 2 increases and so the likelihood of the occurrence of stimulated emission, which leads to gain, is increased. 1.3 × 105 W/cm2 19. This prospect has contributed to interest in developing X-ray lasers. 300 Chapter 12 The Diffraction Grating ui m ⩾1 m 0, b 0 m ⩽1 (a) Unblazed ui m ⩾1 m0 m ⩽1 b0 (b) Blazed Figure 5 In an unblazed reflection grating (a), the diffraction envelope maximum at b = 0 coincides with the zeroth-order interference at m = 0. Radiation over the visible spectrum approximates that of a graybody, with emissivities approaching unity for tightly coiled filaments. (19), (21), and (22), respectively. The half-angle beam divergence uFF = l>1pw02 is valid only in the far field. The violet and red components of the white light leaving point P refract differently at the lens and so converge at different image points, labeled V and R, respectively. In fact, under the conditions for which Eqs. cos u - 2n2 - sin2 u 2 cos u + 2n - sin u P = ITM - ITE ITM + ITE where I stands for the irradiance of either polarization mode. In fact, the Stokes field is generated in a range of frequencies known as the Raman bandwidth of the fiber. Contributing zones are like those included in the chord FG of Figure 15b, but with the spiral length FG moved somewhat toward the lower end. When the responsivity is a function of l, the detector is said to be selective. 14 Assume that in a Mach-Zehnder interferometer (Figure 5), the beam splitter and mirror M3 each transmit 80% and reflect 20% of the incident light. (b) /2, /3, 0, −/2, 0.6 (c) Subtract /2 from each. (32) and (33) can be succinctly summarized by stating that convolution in real space corresponds to multiplication in Fourier space. In a developed photograph, for example, the optical density of the emulsion at each point is a function of the optical energy received there due to the light-sensitive chemical reaction that reduces silver to its metallic form. We employ them here without proof. A diffraction pattern is formed on a screen placed in the focal plane of the lens. 16 a. (a) Wollaston prism. Laser beam Mirror (a) Laser M2 M1 d (b) Pump (c) Resonator (d) Laser medium Properties of Lasers 147 as the He-Ne laser, the most commonly used pump mechanism is an electrical discharge. An understanding of this interaction necessitates a discussion of the quantization of the energies of electromagnetic fields and atoms. Simple applications of the principle are shown in Figure 2 for a plane and spherical wave. 2 COMMUNICATIONS SYSTEM OVERVIEW No application has given greater impetus to the rapid development of fiber optics than has voice or video communication and data transmission. The influence of the sheets with perpendicular scratches on either end of the liquid crystal and the long-term order of the liquid crystal leads to the twisted orientation of the molecules shown in Figure 9a. Determine the location and size of the intermediate image of OP formed by L1 and the final image formed by the system. The distance r may be referred to the distance r0 as follows. Estimate the electric field amplitude and irradiance that would cause the third-order nonlinear contribution to the polarization to be 1% of the linear contribution in a certain mix of b-carotene in ethanol. New York: John Wiley and Sons, 1973. (33) and (34) do not differ greatly, and in citing magnifications, Eq. (33) is most often used. If, when it reaches Mirror 2, its wavefront radius of curvature R1z22 matches the radius of curvature RM2 of Mirror 2, the wave will reflect back on itself, precisely retracing its path and shape through the beam waist and on to Mirror 1. Since the media on either side of the refracting surface are characterized by different refractive indices, however, the isochronous rays are not equal in length. Trace the ray through the cube. This arrangement can also be used as an optical means of measuring the radius of curvature of the lens surface. the line O¿CI¿. The E 2 term is considered negligible in the Pockels effects. Notice that the addition of orthogonal components of linearly polarized light is not unpolarized light, even though unpolarized light is often symbolized by such components. What is the overall operational efficiency (wall-plug efficiency) for this laser? 15 The rotation of polarized light in an optically active medium is found to be approximately proportional to the inverse square of the wavelength. For E 7 OA, n7 = 1.4864 and uc = 42.3°, while for E OA, n = 1.6584 and uc = 37.1°. Figure 7b shows a slightly different view of chromatic aberration evident in the behavior of white light incident on a lens from an off-axis point P. We restrict our discussion to cases where nl>r0 V 1, so that the second term in square brackets is negligible compared with the first. (c) Gregorian telescope. Variations of a signal voltage superimposed on V are transformed into variations in light intensity in such a device, known as a Pockels electro-optic modulator. Pump energy is provided to the system via the 0 to 3 transition. The irradiance of the subject beam is proportional to the square of the magnitude of the complex field amplitude ES . As mentioned earlier, in the absence of pumping, there will be no population inversion between any two energy levels of a laser medium. 4 STANDING WAVES Another important case of superposition arises when a given wave exists in both forward and reverse directions along the same medium. De-excitation of the excited vapor atoms produces a helical of the form of photons of radiation. Thus Eq. (17) describes both the emission and the absorption of a photon by the crystal lattice. Multiple-beam interference takes place when either set is focused to a point by a converging lens, as shown for the transmitted beam. Solid and liquid gain media are typically optically pumped either by a flashlamp or another laser. 12 A presbyopic eye has an accommodation, a near point of 125 cm, and a far point of infinity. (a) He-Cd appears about 1.3 × brighter (b) about 2.4W (a) 900 (b) 85.4 lm/m2 or lx 0.97 nm 4.6 D (a) 8.33 mm; +120 D (b) 42.86 mm; +23.33 D (c) 43.65 mm, measured from the second principal plane; or 42.38 mm from its second vertex; +22.9 D (a) 22.34 mm from cornea (b) 21.60 mm from cornea (a) A = 0.75846, B = 5.1050, C = −0.05011, D = 0.65180 (b) Focal points are 13.01 mm in front and 22.34 mm behind the cornea; principal points are 1.96 mm behind and 2.38 mm behind the cornea. They are called Fraunhofer lines. The rays originate from the same object point, 2 cm above the optical axis and an axial distance of 10 cm from the first surface. One important difference is that the amplitude of the oscillation of the Bessel function decreases as its argument departs from zero. Thus, rays 1, 2 and 3 focus to point A, and rays 4, 5 and 6 focus to point B. As a result the initial gain exceeds the cavity losses and the photon number density begins to grow rapidly. If the screen is moved 75 cm in the process, how far is the object moved? At some distance, so that now the focal plane is always between the ... images formed in a thin film of energy, E2 − E1 = hν. The fiber serves as an optical waveguide to propagate the information with as little distortion and loss of power as possible, shown as the dashed line in Figure 6. ... Vega appears to be the brightest ... Since Jurgen R. If aspects to come from the subject. On Sundays, they simply prayed." The Strange Story of the Quantum Banesh Hoffmann, 1947 INTRODUCTION The words cited above—taken from a 1947 popular primer on the quantum world—delightfully many readers who were part of the modern scene. ... The Michelson interferometer, which uses a beam splitter SP to separate equal-amplitude portions of a spectral input beam from source S and reunite them again after reflection from mirrors M1 and M2. When this occurs, the term anomalous dispersion is used, although there is nothing anomalous about it. A: The image of aperture A backward through L1 is virtual and is shown as A 1œ. Such confusion in high orders is sometimes alleviated by using a second dispersing instrument that spreads the first spectrum again but in a direction orthogonal to the first. A plane wavefront, for example, has a curvature of zero. a. One can show that the resultant contribution from these subzones has an effective phase intermediate between the phases of the zones bounding them.

[illegible]

Example 1 Determine the focal points for a 4-cm thick, biconvex lens with refractive index of 1.52 and radii of curvature of 25 cm, when the lens caps the end of a long cylinder filled with water n = 1.332. The telephoto lens avoids a correspondingly "long" camera by using a positive lens, separated from a second negative lens of shorter focal length, such that the combination remains positive. (46) and (47), calculate z2 and w02 for the newly focused beam. These spurious effects change the cavity length, lead to multimode oscillations, and adversely affect the coherence of the laser. [illegible]

colors, the reconstruction process with white-light illumination can produce a three-dimensional image in full color. more precisely in what follows. Taking the efficiencies into account sequentially as they "occur," how much of the initial 2500 W is available for power in the output beam? E = hn = 16.63 * 10-34 J # s21100 * 106 Hz2 = 6.63 * 10-26 J E = 6.63 * 10-26 Ja 1 eV b = 4.14 * 10-7 eV 1.6 * 10-19 J c. For N large, one need not be concerned about the parity of N. The resultant E-field vector consists of many components 333 334 Chapter 14 Matrix Treatment of Polarization whose amplitudes, frequencies, polarizations, and phases differ. 76 Chapter 3 Optical Instrumentation The actual angular magnification depends, then, on the particular viewer, who will move the simple magnifier until the virtual image is seen comfortably. Window 5 R R 5 cm cm 7. diffraction equations. The eye then sees both in focus together, giving the field of view a sharply defined boundary. Efficient, portable Nd:YAG lasers, pumped by an array of diode lasers, are available. If a multiple-order quartz plate 0.735 mm thick functions as a QWP, what is its order m? Lowpower lasers such as the He-Ne laser often need no external cooling system. Emission wavelength (nm) Light-Emitting Diodes A light-emitting diode (LED) is an important light source quite different from those just described. Relative locations of the refracting surfaces are shown, as are the cardinal points of interest for the eye as a whole. As Figure 1 Schematic defining the parameters for a typical Fresnel diffraction. Thus, the ray paths and times for two different wavelengths also vary with l, leading to pulse broadening. y1 a1 y2 a2 (43) Characteristics of Laser Beams Mirror surface R1 R2 2 m Mirror-lens combination R3 0.64 m w0( ) d 0.7 m Laser cavity t 4 mm External beam waist Determine and w0( ) The heuristic approach used here to develop this relation can be shown to result from a general solution to the wave equation for propagation through media that can be represented by an ABCD matrix.5 The relationship between q2 and q1 in Eq. (43) enables one to describe the new shape of the laser beam after it passes through an arbitrary optical system. The result is that the diffraction maximum now favors a principal maximum of a higher order 1 ƒ m ƒ 7 02, and the grating redirects the bulk of the light energy where it is most useful. Let the scaled transmittance through the Fabry-Perot as a function of the change in the cavity length be as shown in Figure 20a and 20b. The energy carried by an EM wave can be specified in many related ways: the power, power per unit area, and power per unit solid angle, for example. Consider an aperture function formed by two perpendicularly crossed Ronchi rulings. An electromagnetic wave, of course, represents the transmission of energy. In the Raman process the energy lost or gained by the electromagnetic field is accounted for by a change in energy of the molecule. In practice, such images are formed when the observation screen is quite close to the aperture. Q-switching You should be familiar with the quality factor Q as a measure of the loss rate of the cavity. Such a multifocal lens can be used to restore clear vision, to the presbyopic eye, over the full distance range. The refractive index of the plastic is 1.50 and the object is in air. In Figure 7a, parallel rays of light focus nearer the lens, at point V, for violet light and further from the lens, at point R, for red light. In Figure 29, the useful light rays originating at the point O, passing through a thin cover glass and then air to the first element of the objective lens L, make an initial half-angle of aa on the right of the optical axis. ER has its maximum value at all points when cos vt = ; 1, or when vt = 2pnt = a 2p b t = mp T Thus, the outer envelope of the standing wave occurs at times T 3T T , A t = m a b = 0, , T, 2 2 2 where T is the period. 24 Consider the electric field, E = Ex sin1kz - vt + w0x2xN 14 Two waves of the same amplitude, speed, and frequency travel together in the same region of space. New York: Academic Press, 1983. 29 Derive the law of reflection from Fermat's principle by minimizing the distance of an arbitrary (hypothetical) ray from a given source point to a given receiving point. Indeed, were the remainder of the wavelet considered to be effective in propagating the light disturbance, Huygens could not have derived the law of rectilinear propagation from his principle. 19. 39. As a result, the average power output Pav from a Q-switched system is roughly the same as the CW power of the same system. As the irradiance at a given cavity-mode frequency grows, it "reaches" groups of atoms with center frequencies further and further from the cavity-mode frequency. The quartz crystal used by Franken, and many other crystals as well, do not possess inversion symmetry. The zone plate with such transmittance properties is the Fresnel zone plate, which produces multiple focal points along its axis beyond those discussed here for the Gabor zone plate. Because the edges of optical images are blurred by diffraction, the phenomenon leads to a fundamental limitation in instrument resolution. The diameter of the eyepiece field lens is 2 cm. 450 Chapter 20 Aberration Theory rays through the section ss¿ of a single lens. Such processes provide a means of producing intense and coherent electromagnetic radiation at frequencies at which there are no efficient laser transitions. Changes in angle occur at each refraction, such as at points 1 through 5, and at each reflection, such as at point 6. For the case N = 8, four such peaks, at a = 0, p, 2p, and 3p are shown in Figure 15a. 16 Determine collimated beam lengths 2z0 for a TEM00 Nd:YAG laser beam 1l = 1.064 mm2 focused by lenses of aperture diameters D = 1 cm, 2 cm, 3 cm, and 5 cm, respectively. The distance from the source S to a representative point O on the wavefront at the aperture is r¿, and the distance from the point O to a representative point P in the field is r. Lee, S. Grating Wadsworth mount for a concave space occupied by this spectrograph can be quite large. Light of irradiance I0 is incident on an atomic medium from the left as shown. For example, an ideal aspheric wavefront can be created synthetically to serve as a model against which a mirror may be shaped, using interference between the two surfaces as a guide to making appropriate corrections. A population inversion between two appropriate energy levels in the laser medium. Could you have used the approximate formulas w02 fl>pw01 and z2 = f in this instance? Measured values for these constants, e0 = 8.8542 * 10-12 1C # s22>kg # m3 and m0 = 4p * 10-7 kg # m>1A # s22, provide an indirect method of determining the speed of electromagnetic waves in free space and yield a value of c = 2.998 * 108 m>s. Determine the irradiance at the film. In Figure 2, we specify a particular optical system consisting of two lenses, L1 and L2, with an aperture A placed between them, as shown. The negative sign is introduced, as usual, to indicate that the image is inverted in Figure 31, where fe 7 0, and is erect in Figure 32, where fe 6 0. To image an actual object, this requirement must hold for every object point and its conjugate image point. Conductive Keratoplasty (CK) An alternate corrective procedure, known as conductive keratoplasty (CK), is currently available to patients over 40 years of age with mild amounts of hyperopia—up to about + 2.5 diopters. In between successive peaks there are shown N - 2 = 6 secondary peaks. The powers of the two lenses for the yellow center of the visible spectrum, conveniently represented by the Fraunhofer wavelength, lD = 587.6 nm, are P1D = 1 1 1 = 1n1D - 12a b = 1n1D - 12K1 r11 r12 f1D (33) P2D = 1 1 1 = 1n2D - 12a b = 1n2D - 12K2 r21 r22 f2D (34) (35) Here, f1 and f2 are the focal lengths of the two lenses in the doublet. 22 Design an achromatic doublet of 5-cm focal length using 638/555 crown and 805/255 flint glass. Material dispersion for pure silica 200 175 150 M (ps/nm-km) 125 100 75 50 25 Figure 13 Material dispersion in pure silica. (b) Forces acting on a dipole when the electric field has the direction indicated. Assume a LED source with a spectral width of 25 nm. Boundary Conditions for TE Waves As mentioned earlier, TE waves have electric fields that are perpendicular to the plane of incidence and therefore are parallel to the boundary plane separating the two media. The number N of standing wave modes that will likely be present in the laser output is the ratio of the frequency range supported by the gain medium to the separation between standing wave modes: N = ¢ngain nm + 1 - nm = 1.5 * 109 Hz = 3 5 * 108 Hz Unlike traveling waves, standing waves transmit no energy. Optical filtering is the process of intentionally blocking certain portions—that is, certain spatial frequencies—present in the diffraction pattern, to manipulate the image. It is important to note that although the irradiance increases with each pass through the inverted gain medium, it decreases each time it encounters the output mirror of the resonator. We have achieved one of our objectives: The irradiance at P is dependent on the correlation function ≠1t2 involving the source field. If the zone plate or grating provides a square wave type of transmittance, 1 More precisely, the transmittance can be expressed as A + B cos21ar22, where A, B, and a are constants. For small focal lengths, Eqs. Such accurate imaging is also possible when the secondary mirror is concave ellipsoidal, as in the Gregorian telescope (Figure 34c). Fresnel Equations 5 Show that the Fresnel equations, Eqs. Source: Adapted with permission from Mathew Alpern, "The Eyes and Vision," Table 1, Section 12, in Handbook of Optics (New York: McGraw-Hill Book Company, 1978). For an antireflection coating of this type, the reduced reflected light near the middle of the spectrum results in a predominance of the blue and red ends of the spectrum, so that the coatings appear purple in reflected light. Calculation then gives LED: LD: d1t>L2 = 1100 ps>nm-km2 120 nm2 = 2 ns>km d1t>L2 = 1100 ps>nm-km2 11 nm2 = 0.1 ns>km At 0.82 mm, the LD is 20 times better than the LED, as a direct result of its superior monochromaticity. A., and S. In effect, the polarizeranalyzer pair transforms phase modulation into amplitude modulation. What is the significance of this result? The distances from S1 and S2 to any point P on a bright fringe surface differ by an integral number of wavelengths. 6 A transmission grating having 16,000 lines/in. 12 A sphere 5 cm in diameter has a small scratch on its surface. If the phase difference between light waves arriving at P from neighboring slits is p, determine the ratio IP>Imax . Example 1 Determine the specific rotation produced by a 1-mm-thick quartz plate at a wavelength of 396.8 nm. The first question to be answered is: Which element serves as the effective AS for the whole system? The incident plane wavefronts of light are of wavelength 546 nm. In either case, the length L of the telescope is given by L = fo + fe (49) permitting a short Galilean telescope, a circumstance that makes this design convenient in the opera glass. The laser output consists of a number of modes with frequencies spread across the gain bandwidth of the lasing transition. As a consequence of this assumption, two harmonic waves in the medium obey the principle of superposition, traveling without distortion due to the medium itself or as a result of the mutual interference of the waves, regardless of the intensity of the light. What is the fringe visibility in a region where the irradiance of the reference beam is three times that of the subject beam? 10 DOPPLER EFFECT The familiar Doppler effect for sound waves has its counterpart in light waves, but with an important difference. The medium is pumped by a laser, of irradiance Ip , that is resonant with the 3-to-1 transition. 23 Geometrical Optics rays reflected in various directions and thus a diffuse scattering of the originally parallel rays of light. Figure 17a shows how this circumstance can be put to practical use in determining the quality of the spherical surface of a lens, for example, in an arrangement in which the Fizeau fringes have come to be referred to as Newton's rings. This requirement gives n 7 2n or n 7 1 Thus the minimum optical signal that can be extracted from the inherent quantum noise in an ideal laser field must contain, on average, at least one photon per detector sampling time. Suppose the film F to be measured has a thickness d. The direction of energy flow depends critically on the phase of the fundamental field, which drives the nonlinear polarization, relative to the phase of the second harmonic field, which is absorbed and emitted by the dipole oscillations comprising the nonlinear polarization. (c) Image of the frustule after applying a spatial filter as indicated in (d). Using Eq. (4) and the values of the ground state and first excited state energies of hydrogen found from Eq. (2) gives P2 -5 # = e-1E2 - E12>kBT = e-1-3.4 + 13.62>18.62 * 10 2932 = 4.1 * 10-176 ! P1 That is, it is very likely that all of the hydrogen atoms will be in the ground electronic state at room temperature. It can be shown that the number N of coherent oscillators responsible for the reflected radiation is proportional to l2, so that the radiated power is proportional to l4, canceling the 1>l4 dependence of isolated Rayleigh scatterers. 2 HARMONIC WAVES Of special importance are harmonic waves that involve the sine or cosine functions, y sin l y = Acos[k1x ; yt2] A x t constant (a) y T A t x constant (b) Figure 2 Extension of a sine wave in space and time. A small object of dimension h, when examined by the unaided eye, is assumed to be held at the near point of the normal eye—nearest position of distinct vision—at position (a), 25 cm from the eye. It is found that when a vertical wire grid, whose spacing is much smaller than the wavelength, intercepts microwaves with vertical linear polarization, little or no radiation is transmitted. Assume light of wavelength 500 nm is incident on the interface at an angle of 60°. We show in the next section that if two source points S1 and S2 , as in Figure 12, are separated by a distance s and if light of wavelength l from these sources is observed at a distance r away, there will be a region of high spatial coherence of dimension ls , given by ls 6 l u (35) where u is the angle subtended by the point sources at the observation point P. Find the lifetime-broadening contribution to the homogeneous linewidth for this transition if the lifetime of the upper lasing level is 10 ms and that of the lower lasing level is 0.1 ms. These are represented by the amplitude BE on the Cornu spiral. Although derived here for an even number N of slits, the result expressed by Eq. (32) is valid also for N odd (see problem 21). 206 Chapter 8 Optical Interferometry Solution Using Eq. (27) and noting from Figure 10 that Tmin = 0.05, the coefficient of finesse is found to be F = Tmax - Tmin 1 - 0.05 L = 19 Tmin 0.05 The finesse can be found either by extracting the FWHM from Figure 10 and using Eq. (34), F = dfsr FWHM L 2p = 6.8 2.03 - 1.11 or by using Eq. (29), F = p219 p2F L = 6.8 2 2 The mirror reflection coefficient can be obtained from Eq. (29), F = pr = 6.8 11 - r22 Rearranging gives 6.8r2 + pr - 6.8 = 0 Taking the positive root of this quadratic reveals r L 0.80 6 SCANNING FABRY-PEROT INTERFEROMETER As noted earlier, a Fabry-Perot cavity is commonly used as a scanning interferometer. Thus, letting ex = 0, M = c eiex 0 0 1 iey d = c e 0 ip>4 d 0 e This matrix then operates on the Jones vector representing the left-circularly polarized light: c 1 0 ip>4 d c 0 e 1 1 1 d = c ip>4 d = c i3p>4 d i ie e The resultant Jones vector indicates that the light is elliptically polarized, and the components are out of phase by 3p>4. Now let us require that the diffracted beam satisfy both the condition of specular reflection from the groove face and the condition for a principal maximum in the mth order, that is, u = um. The contributing zones as "seen" from P¿ thus include zones from z = + 0.1 mm to z = 0 in the upper half of its wavefront and from z = 0 to z = - 0.9 mm in the lower half. Thus, show that optical density is equal to -log10 T. 24 A homemade compound microscope has, as objective and eyepiece, thin lenses of focal lengths 1 cm and 3 cm, respectively. There exists a variety of situations in which such interference can take place, affecting the nature of the interference pattern and the conditions under which it can be observed. Figure 20a shows the image, as well as several rays, which are now determined. In regions close to the symmetry axis, the Gaussian beam can be adequately described by planar waveforms. Other applications make use of the beam deflection capabilities of the AO effect. That is, the photon lifetime of a cavity is the time interval 1t - t02 over which the energy stored in a cavity without gain or input decays to 1/e of its initial value. 3 A driveway is illuminated at night by identical lamps at the top of two poles 30 ft high and 40 ft apart. Show that the actual distance xs a ray travels during one skip distance is given by xs = n1d sin u where u is the entrance angle and the fiber is used in air. Furthermore, allowing R : q yields the appropriate refraction matrix for a plane interface. In general, B B B k ¿ = k ; kS k k sin u kS u k sin u With the plus sign, we interpret this to mean that an incident photon combines with a phonon to produce the diffracted photon; with the negative sign, the incident photon is considered to yield an additional phonon to the acoustic wave, as well as a photon to the diffracted beam. 1 d. However, many scientists would agree, a comfortable understanding of the true nature of light is somewhat more elusive. Note that a bold dot is used to denote directions perpendicular to the plane of incidence. The energy of the driving wave, however, is gradually dissipated as the wave advances through the absorber, so that the efficiency of the dichroic absorber is a function of the thickness. An eye placed near the ocular views an image at infinity but with an angular magnification given by the ratio of the 83 Optical Instrumentation Final image Exit pupil (eyepoint) Real intermediate image Exit pupil of objective Specimen Condenser diaphragm Field diaphragm Light source Imaging beam path Illuminating beam path (a) (b) Figure 30 (a) Standard microscope illustrating Koehler illumination. The diffracted light is incident on a second concave mirror, which then focuses the spectrum at the exit slit. In the general case, the equation that must be satisfied by the blaze angle is found by combining Eqs. (See problem 8.) 11 Show that if L = 11>sœ 2 - 11>spœ 2, setting dL>ds = 0 produces the condition for minimum spherical aberration: s = - 21n2 - 12p n + 2 12 A positive lens of index 1.50 and focal length 30 cm is "bent" to produce Coddington shape factors of 0.700 and 3.00. 10 Light from a mercury lamp falls on the beam splitter of a student Michelson spectrometer. In the general case, pulses spread and distort as they propagate due to the differing speeds of the 2 For reviews of this phenomenon, see Kirk T. The gain cell represented by the upper curve has twice the smallsignal gain coefficient of the cells represented by the lower two curves, and as a consequence the output irradiance shown in the upper curve is significantly larger, even for short gain lengths, than those shown in the lower curves. Chromatic Aberration Chromatic aberration results because the index of refraction of a material differs for different wavelengths. After advancing through the subzones of the second half-period zone, the phase changes by another p and the last phasor ends at B. These tightly bound electrons are said to occupy states in the valence band of electronic energy states of the material. The locus of the line images S and T for various object points P are paraboloidal surfaces, as illustrated in Figure 9c. Used commonly in radio and television broadcasts, they include the AM radio band (540–1600 kHz) with wavelengths ranging from 188 to 556 m as well as the FM radio band (88–108 MHz) with wavelengths from 2.78 to 3.41 m. If the alignment is such that the air space between M1¿ and M2 in Figure 1b is a wedge, fringes of equal thickness may be seen localized at the mirrors. Notice that shorter wavelengths have larger refractive indices and, therefore, smaller speeds in the prism. Since the line width of spectral sources can be measured, average coherence times and coherent lengths may be surmised. Recalling that N2 and Np are densities and that the atomic population is spread through the volume Vg of the gain medium, whereas the photons are distributed throughout the field in the cavity occupying an effective volume Vc , we write dNp dt = -≠Np + 1Vg>Vc2scNpN2 (55) Here, ≠ is the cavity loss rate and the Vg>Vc is approximately the ratio of the length of the gain cell to the perimeter P of the ring cavity. (a) 0.35 mm (b) 1 m 8. Estimate the difference l2 - l1 in wavelength of the two components presuming that the overlapping transmittance peaks have the same mode number, m2 = m1 = m. Calculate the path length difference ¢L required to perform this task. The only difference lies in the prefactors that modify the phases of all the elements of the Jones vector in the same way and hence do not affect interpretation of the results. For a beam such that w01 is approximately equal to the radius of the lens, multiplying the numerator and denominator of Eq. (48) by 2 and using the definition f# K f>D for the f-number of the lens, where D is the lens diameter, leads to w02 = 2fl 2lf# = p p12w012 (50) In general, then, a smaller f# of the focusing lens produces a smaller beam waist at the focused spot. In Figure 2a, the repetitive spatial unit of the wave is shown as the wavelength l. So, we define a subject beam scaled irradiance IS as, IS = ƒ ES ƒ 2 = E *SES = [s1x, y2]2 (5) This scaled irradiance function thus includes no information regarding phase of the subject beam. By isotropic we mean that the relevant physical properties we consider are independent of direction in the medium, so that we may treat the physical constants as scalar quantities. Seizing the initiative, we claim that this correspondence4 can be extended to other basic laws, for example, the simple lens law. For such a situation, the irradiance Properties of Lasers 157 1 m from a He-Ne laser with a much smaller output power of 1 mW would be I = P>A = 0.001 W p10.002 m22 = 79.6 W>m2 Irradiance 1 m from a 1-mW He-Ne laser High-power lasers may have a continuous output of 105 W with a beam radius of 1 cm. Example 2 As an extended example of refraction by spherical surfaces, refer to Figure 20. The energy of a plane, electromagnetic wave propagates in the direction of the Poynting vector, given by B B B S = e0c2E * B (1) The magnitudes of electric and magnetic fields in the wave are related by E = yB (2) where the wave speed is related to the the refractive index n by c y n = (3) The wave speed in vacuum is a constant, equal to c = 1 1e0m0 (4) where e0 and m0 are the permittivity and permeability, respectively, of free space. Superposition of Waves 125 ⩽1 ⩾1 cos (kg x0 ⩾ vg t) cos (kp x0 ⩾ vpt) (a) Envelope moves with group velocity yg. Scattering that occurs from larger particles2 such as those found in clouds, fog, and powdered materials such as sugar appears as white light, in contrast to Rayleigh scattering. Such detectors possess superior sensitivity in the visible and ultraviolet spectral ranges. These two lower curves show that, for gain cell lengths L short enough that the irradiance in the cell remains well below the saturation value, the output irradiance from the cell is nearly independent of the saturation irradiance. There are a number of designs possible; we describe briefly a few of the more common ones. An object is situated at a distance of 1.20 cm from the objective. Tracking the irradiance from the output end around the ring to the input end leads to the relation I0 = SIL (42) Here, S is the fraction of the irradiance that survives the trip around the cavity from the output to the input of the gain cell. E = E0 cos1kz - vt2xN - E0 cos1kz - vt2yN z z B b. s1 30 10 s2 30 s1 40 (b) VO2 RI1 35 Geometrical Optics indicating an inverted image, equal in size to that of the object. How does the emergent light vary as a function of u? Then by opening the aperture wider to admit the second zone as well, the additional light produces almost zero amplitude at P! Now remove the opaque shield altogether, so that all zones of an unobstructed wavefront contribute. The pulse repetition time in a Q-switched system is typically on the order of 1 ms. F = Coefficient of Finesse Finesse 11 - r222 T = p 2F pr = 2 1 - r2 F = Quality Factor 4r2 Q = n F nfsr 1 1 + F sin21d>22 F = Q = F = FSR FWHM R K n 2¢n1>2 Tmax - Tmin Tmin 2dF l = ¢lmin l Q L v = vtp ≠ TABLE 2 Fabry-Perot parameters for a cavity with a nominal spacing of d = 5 cm, a nominal input wavelength of l = 500 nm, and a nominal frequency of n = 6 # 1014 Hz. Photon lifetime and FWHM are quantities that are not applicable (NA) if the reflection coefficient is too low. (a) 27.8 mm (b) ƒ/3.1, ƒ/5.4, ƒ/9.4 (c) 16.0, 9.26, 5.35 mm (d) 0.03, 0.09, 0.27 s 22. It can be shown1 that, in general, three angularly distinct beams result so that three distinct spots appear in the image plane. Then, from Eq. (52), ¢nD = a 1>2 8 * 1.38 * 10-23 * 3000 3 * 108 ln122b Hz -26 8 2 488 * 10-9 6.64 * 10 13 * 10 2 = 3.8 * 109 Hz = 3.8 GHz There are many other important mechanisms leading to inhomogeneous broadening. It is stimulated emission that makes possible the amplification of light within a laser system. 12. As v is varied, there will be a series of resonance frequencies characteristic of the material. Use the ideal four-level gain medium relation given as Eq. (38) together with the definition of the effective pump rate density given following Eq. (33) to estimate the pump irradiance required to sustain a small-signal gain coefficient of 0.01/cm and 1/cm. An Nd:YAG system can provide a high power, good beam quality CW output, and can be either mode-locked or Q-switched. This ray leaves point P, passes through F, strikes a concave mirror, and is reflected as a ray parallel to the optical axis, as in Figure 17a. "Generation of Optical Harmonics," Phys. Thrierr, Atlas of Optical Phenomenon, Plate 33, Berlin: SpringerVerlag, 1962.) 316 Chapter 13 Fresnel Diffraction 5 PHASE SHIFT OF THE DIFFRACTED LIGHT The first phasor a1 in Figure 5 is drawn, rather arbitrarily, in a horizontal direction, and the other phasors are then related to it. This aperture is usually referred to by photographers as f/8. Sodium or mercury gas-discharge lamp sources are far more monochromatic and coherent. This path difference ¢s is ¢s L 2 # 50¢L = 100hL Here, ¢L = hL is the difference in the lengths of the interferometer arms (of nominal length L) induced by the gravitational wave. Further, let the population densities of the two atomic energy levels be N2 and N1 , respectively. 7 TIME-DEPENDENT PHENOMENA In the previous sections of this chapter, we have developed a means for predicting the steady-state output irradiance from a laser. In forming the last equality we have made use of the fundamental definition of irradiance to form I1P = e0c8E21P9 and I2P = e0c8E22P9. The astronomical telescope may be modified to produce an erect image by the insertion of a third positive lens whose function is simply to invert the intermediate image, but this lengthens the telescope by at least four times the focal length of the additional lens. (b) Profile of a step-index fiber, in which the core index is constant and slightly greater than that of the cladding. What is the nature of the product light? Level E2 is labeled as the "upper laser level." This is special in the sense that it has a long lifetime. When E is to the left of I, as shown for the case of a positive lens, the spherical aberration is positive; for a negative lens, E falls to the right of I, and the spherical aberration is considered negative. However, as we will discuss, for real fields, which are not perfectly monochromatic, care must be taken in treating this time average. Notice that we have defined the frequency linewidth ¢n associated with transitions between a pair of atomic levels as ¢n = ¢En + ¢Em h (3) 135 It is common to refer to the frequency n0 as the frequency at line center. The spontaneous emission rate per unit volume is RSp. Em. = A21N2 (11) Here, A21 is the Einstein A coefficient for the 2 to 1 transition. The sensitive material is an emulsion of silver halide crystals or grains. Thrierr, Atlas of Optical Phenomenon, Plate 32, Berlin: Springer-Verlag, 1962.) 1.0 y ⩾2.0 H D ⩾1.0 B 0.5 (c) (d) upper zones (along the wavefront above O¿) plus some of the first lower zones (between O and O¿) contribute. Without deriving this Rayleigh scattering law, we can make the following hand-waving argument: The electric field of a dipole with a charge e accelerating back and forth along a B B d2 r >dt2 = - v2 r , then the acceleraline isB proportional to the acceleration. (5) and (6) will constructively interfere if the difference 1a2 - a12 in their phase constants is m12p2, where m is an integer. The light refracted into the water is intercepted by the top flat surface of a block of glass with index of 1.50. Mere amplification of a signal is not useful when it does not distinguish between signal and noise and results in the same signal-to-noise ratio, just as the mere magnification of an optical image is not useful since it does not clarify the object details. 515 516 Chapter 24 Nonlinear Optics and the Modulation of Light Optic axis Direction of matching Sign of x2 Figure 2 Phase matching techniques. Those that do not leave through the output mirror are reflected, recycling back and forth through the cavity gain medium. PEDROTTI LENO S. 68, No. 293 (2000) and Barbara Gross Levi, Phys. The air-flow pattern is revealed by the fringe pattern. The specified focal length of the 445 446 Chapter 20 Aberration Theory lens is due to the intersection of paraxial rays for which h : 0. Figure 14c and d contains photographs of a single-slit pattern and a double-slit pattern with the same slit width. As the field point P approaches the zone plate along the axis, the same zonal area of radius R1 encompasses more halfperiod zones. Fermat's principle, applied to the second component l¿, gives FT + TW - ¢s = 1n - ¢n2b Subtracting the last two equations, we conclude ¢s = b ¢n (19) or, introducing the dispersion, ¢s = b a dn b ¢l dl (20) Equation (20) now relates the path difference ¢s to the wavelength difference ¢l. The electric force on the charged particle is along the direction of the polarization of the wave and so must be perpendicular to the direction of propagation of the wave. Planes1 normal to the axis at these points are called the cardinal planes. We now provide brief sketches of the various invisible regions of the electromagnetic spectrum. Show that for the two-level absorptive medium considered in Section 2, IS,abs = hn¿ 2st2 where t2 = 1>A 21 . 7 a. Show that the total optical density of several film layers is just the sum of their individual optical densities. In fact, using 11>s2 + 11>s¿2 = 1>f, with s¿ = -15 cm (myopic near point for person) and f = - 100 cm, solving for s, one finds that objects can be brought in as close as 17.6 cm from the eye and still be seen clearly. The minimum separation, xmin , of two just-resolved objects near the focal plane of the lens of diameter D is then given by xmin = f ¢umin = f a 1.22l b D The ratio D/f is the numerical aperture, with a typical value of 1.2 for a good oil-immersion objective. Interference of Mutually Coherent Beams If light from the same laser source is split and then recombined at a detector, the time average in Eq. (13) need not be zero. If they qualify, give the magnitude and direction of the wave velocity. 2 Show that in a nearly transparent medium, the absorption coefficient is related to the conductivity and refractive index by 1377 Æ2s a = nR 3 Calculate and/or plot real and imaginary parts of the refractive index for a dielectric given the frictional parameter g, the resonant frequency v0 , and the dipole density N. Find the aplanatic points for a spherical surface of + 8 cm separating two media of refractive indices 1.36 and 1.70, respectively. The amplitudes of the electric field reflected internally and externally from the film of Figure 10 are then equal, assuming a nonabsorbing film, if the relative indices are equivalent for these cases, that is, if nf n0 = ns nf or nf = 2n0ns (28) Since usually n0 = 1, the requirement that reflected beams be of equal amplitude is met by choosing a film whose refractive index is the square root of the substrate's refractive index. 4 The angle between the signal and reference beams during construction of a hologram is 20°. Thus, beam 4 includes rays that have traveled different optical paths and will demonstrate interference. Example 2 A myopic person (without astigmatism) has a far point of 100 cm and a near point of 15 cm. A thin lens combines two such surfaces, each of which contributes to the total spherical aberration. A point object S sends rays toward a plane mirror, which reflect as shown. Before analyzing the resulting expression, we will recast the solution into a more easily interpreted form. (20) to (23) and by (b) using the corresponding equations for the reflection coefficients, together with the relationships between reflection and transmission coefficients implied by Eqs. Figure 11 illustrates the working principle of a Soleil-Babinet compensator. Alternatively, if light of wavelength l0 in air is incident on the film at angle u0 one can write ml0 = d sin u0 Since l = l0 /n and sin u0 = sin u/n. Determine the distance between (a) the central maximum and first minimum and (b) the first and second minima. Today the typical grating master is made by diamond-point ruling of grooves into a low-expansion glass base or into a film of aluminum or gold that has been vacuum-evaporated onto the glass base. When a distant point source of light is observed looking through the plate, a diffuse halo is seen whose angular width is about 2°. In Figure 16c, a construction is shown that allows the determination of the transverse magnification. Those remaining equations are Ea = E0 + Er1 (27) Eb = Et2 (28) Ba = g01E0 - Er12 (29) Bb = gsEt2 (30) For the fields represented by Eqs. In steady state, the losses due to imperfect reflection and transmission at the mirrors must be, in each round-trip, offset by the increase in irradiance that results from interaction with the gain medium. (a) 1 − e−2a 2 /w2 (b) 1 − (1 + 2a2 /w2)e−2a 2 (c) 1 − (1 + 2a2 /w2 + 12 (2a2 /w2))e−2a 2 2 /w 2 /w2 (d) 1 − (1 + 23 (2a2 /w2) + 12 (2a2 /w2))e−2a /w 23. See Figure 7 for a sketch of this type of lamp and its housing. 2 FREE SPECTRAL RANGE OF A GRATING For diffraction gratings, the nonoverlapping wavelength range in a particular order is called the free spectral range, lfsr . When j = 1, for example, Eq. (31) reduces to the double-slit case, Eq. (23). For angle of incidence u1 6 uc both refraction and reflection occur. If a direction through the crystal is chosen such that n2v for the E-ray equals nv for the ordinary (O) ray, the fundamental and second harmonic waves remain in step and the crystal can be a centimeter or so thick. (b) Mach-Zehnder fiber interferometer used as a wavelength demultiplexer. This is the so-called Raman-Nath regime.13 If the crystal is thicker, regions of higher refractive index represent planes normal to the direction of the acoustic wave, as suggested in Figure 11. The core index is 1.48. In all cases n0 = 1 and ns = 1.52. Note that the resulting irradiance in Figure 15b reflects the presence of the limiting diffraction envelope. The eyes, in conjunction with the brain, constitute a truly remarkable biooptical system. Another interesting application of polarization by reflection is the Brewster window. Such image points are called aplanatic points. When a collimating lens is used between source and interferometer, as shown in Figure 7a, every set of parallel beams entering the etalon must arise from the same source point. The detector output is then handled by a signal processor, whose function is to recapture the original electrical signal from the carrier, a process that involves filtering and amplification and, possibly, a digital-to-analog conversion. (a) At laser turn on the gain coefficient has its small-signal value g01n2 and six cavity modes are above threshold. New York: McGraw-Hill Book Company, 1966. Steady state is reached when only the cavity mode with the frequency closest to the line center frequency n0 experiences 567 Laser Operation a gain coefficient equal to the threshold value. The wave is modified by the frosted glass in a nonuniform manner, but its phase conjugate—after reflection by the PCM—exactly retraces its path and reverses its modifications, so that the return passage through the distorting medium undoes or "heals" the original distortion. E = E0 sin1kz - vt2xN + E0 sina kz - vt - byN 4 p B d. Do a ray diagram for some object. Unless the reflectance of the film is large, a good approximation to the more complex situation of multiple reflection (Section 9) is to consider only the first two emerging beams. The first term P1 in Eq. (3) represents linear optics in which the polarizaB B tion of the medium is simply proportional to the E-field. Consequently, in the presence of modal distortion, the advantage of superior monochromaticity of a LD over a LED is lost. The different energy levels of atoms are associated with different configurations of the electrons that surround the nucleus of the atom. Estimate the size of the particles. We now present a treatment of image formation that employs matrices to describe changes in the height and angle of a ray as it makes its way by successive reflections and refractions through an optical system. Other extrinsic losses occur as light is coupled into and out of the fiber. The developed plate is called a Gabor zone plate—or zone lens—with circular transmitting zones, whose transmittance is a gradually varying function of radius r. A one-to-one correspondence then exists between source and screen points. 5 SIMPLE MAGNIFIERS AND EYEPIECES The simple magnifier is essentially a positive lens used to read small print, in which case it is often called a reading glass, or to assist the eye in examining small detail in a real object. The variations in transverse amplitude deviate more and more from a pure Gaussian form with higher [illegible]

axis SOP. Ch. 31. Visual Acuity The ability to see detail clearly and to perceive real differences in spatial orientation of objects is related to visual acuity. (a) 11,950 and 21,240 W/m2 (b) 12,960 W/m2 2 (d) 0.95 (c) 33,200 W/m 0.86, 0 0.8; 3.73/1 (b) 1.78, 2.55, 4.00, 13.9 Lloyd's mirror interference fringes are produced, aligned parallel to the slit, and separated by 0.273 mm. This important feature is also shown in Figure 30, where the line image is real for a cylindrical convex lens and virtual for a cylindrical concave lens. When photons of energy exceeding the band-gap energy of the semiconductor are absorbed in the vicinity of the junction, the created electronhole pairs are separated by the electric field in the junction region, causing a change in voltage, the photovoltaic effect. Fyodorov, who treated the youngster did not hold out much hope for restored vision in the eye, even though the cuts were superficial. Similarly, when ex 7 ey , M = eip>4 c 1 0 0 d -i QWP, SA horizontal (18) Corresponding matrices for half-wave plates (HWP), where ƒ ex - ey ƒ = p, are given by M = c e -ip>2 c eip>2 0 0 1 d = e -ip>2 c eip>2 0 M = c eip>2 0 -ip>2 d = eip>2 c 0 e 1 0 0 d -1 0 d -1 HWP, SA vertical (19) HWP, SA horizontal (20) The elements of the matrices are identical in this case, since advancement of phase by p is physically equivalent to retardation by p. Determine the longitudinal and lateral spherical ray aberrations for light entering at an aperture height of h = 1 cm. For sizable incident irradiances, the rate of spontaneous emission into the direction of the beam is much less than the stimulated emission and stimulated absorption rates, and so spontaneous emission makes a negligible contribution to the net rate of photon production. When the spacing is fixed, the instrument is often referred to as an etalon. The angle u is the Bragg angle. Therefore, the lateral magnification is less for aperture position (1) than for aperture position (2). The significance of Eq. (37) is apparent in the case of Young's doubleslit experiment, where an extended source is used together with a single slit to render the light striking the double slit reasonably coherent, as in Figure 14. The physical operation of opening the diaphragm is thus analogous mathematically to the systematic inclusion of higher and higher frequency terms in the Fourier series representing the aperture function. (b) Irradiance for the double slit of (a). Proceeding, g0 dI = gI = I dz 1 + I>IS (40) Separating variables and integrating both sides of the resulting relation gives IL ⌡ I0 a 1 1 + b dI = g0 I IS L ⌡ dz 0 Integration gives ln a IL 1 b + 1IL - I02 = g0L I0 IS (41) The important result given in Eq. (41) is a transcendental relation that can be numerically solved for the output irradiance IL given the input irradiance and the characteristics of the gain medium, g0 , L and IS . In contrast, a metallurgical objective is designed without such compensation. Determine values of film thickness and (hypothetical) refractive index that will produce a nonreflecting film for normally incident light of 500 nm. 2 2 2 x Node t 0, T, 2T, . This procedure is cumbersome and the resulting expression inelegant, and so we leave this as an unlisted problem for the ambitious student. We permit the two waves to differ in amplitude and phase. At time t + t, the right-going intracavity field E1+1t + t2 can be formed as the sum of two parts. Fourier Optics 3 The optical density of film is defined as the common logarithm of its opacity. The combined wavefront and irradiance variation of such a typical laser beam passing through a converging lens might appear as shown in Figure 1. More importantly, this approach also leads to the Fresnel equations, which describe the fraction of incident energy transmitted or reflected at a plane surface. Steward, E. (a) A = 0.9764, B = 0.9676, C = 0.009182, D = 1.033 (b) f1 = 108.9 cm, f2 = −108.9 cm, p = 112.5 cm, q = −106.3 cm, r = 3.62 cm, s = 2.57 cm (c) −100 cm 15. for 20/20; 0.065 in. Cotter. The component E7 , which is parallel to the OA of the crystal, causes electrons in the base plane to oscillate along a direction perpendicular to the plane, whereas its orthogonal counterpart E causes oscillations within the plane. On a screen, the fourth minimum of the 436-nm light coincides with the third maximum of the other light. Each of the small phasors represents the contribution from one subzone. Scattering and other mechanisms lead to a coupling between the orthogonal polarization modes. When level E2 does decay, say by spontaneous emission, it does so to level E1 , labeled the "lower laser level." Level E1 is an ordinary level that decays to the ground state quite rapidly, so the population N1 cannot build to a large value. It is interesting to note that human color sensation is a function of illumination and is almost totally absent at lower levels of illumination. The fringe pattern shifts by an amount ¢x at the film edge. 27 A laser beam from a 1-mW He-Ne laser (632.8 nm) is directed onto a parallel film with an incident angle of 45°. (d) Nonparaxial rays from object point P near the axis form an image at P¿, subject to the Abbe sine condition. The echelle is positioned directly over the slit-to-mirror path, but the plate is offset in a horizontal direction. Making use of Eq. (10), we also determine that a = - 45°. We follow this with a brief overview of aberrations and then examine in turn, the optics and operation of prisms, cameras, eyepieces, microscopes, and telescopes. Such sources are available at operating temperatures from that of liquid nitrogen 1 - 196°C2 to 3000°C. What wavelength is reinforced in reflected light when white light is incident normally on the hologram? Many sources of noise in quantum detectors exist,2 including shot noise or quantum noise, which arises because of the statistical nature of the conversion of a photon in the incident field to an electron in the detector system. For example, a Littrow grating can be used as a wavelength-selective mirror to ensure that only one of several laser lines experiences low loss in a laser cavity. (27) and (28) leads to, in steady state, dN2 sI = 0 = Rp2 - k2N2 1N - N12 dt hn¿ 2 (32) dN1 sI = 0 = Rp1 + k21N2 - k10N1 + 1N - N12 dt hn¿ 2 (33) where we have defined the effective pump rate densities Rp2 = k32 spIp a N b k3 hnp T Rp1 = k31 spIp a N b k3 hnp T Equations (32) and (33) can be solved for the population inversion, giving Ninv = N2 - N1 = 11 - k21>k102Rp2 - 1k2>k102Rp1 k2 + 11 + k20>k1021sI>hn¿2 (34) 559 Laser Operation When describing gain media, Eq. (22) is often recast by defining a gain coefficient g as g = s1N2 - N12 = sNinv (35) dI = gI dz (36) so that It is important to note that the gain coefficient depends on the irradiance I, since the population inversion is, in general, dependent on the irradiance. Free electrons respond in this manner. However, when the bundles are large, as shown in (b), spherical aberration occurs, which produces a shorter focus for rays reflecting from the outer zones of the mirror relative to the optical axis of the bundle. According to our definition of the ExP, the exit pupil is the optical conjugate of the AS; the ExP and AS are conjugate planes. Several basic designs for reflecting telescopes are shown in Figure 34. Such irradiance levels are readily developed with the help of beam expanders and suitable focusing optics. We now interpret the three terms in Eq. (9) as the reconstruction of three distinct beams from the hologram. E 01 (21) Some time after the incident field is first directed onto the cavity, the intracavity electric field will settle down to a constant steady-state value. Let us return to our earlier development in this chapter and generalize Eq. (10), which we first guessed to have the form 2 U1x, y, z2 = E0eJ[p1z2 + k1x + y22>2q1z2] as U1x, y, z2 = E0g a y x 2 2 b h a bei[p1z2 + k1x + y 2>2q1z2] w w (51) The presence of the functions g(x/w(z)) and h(y/w(z)) admit waveforms that do not have cylindrical symmetry. When reflection is internal, Figure 5, we conclude that a p-phase shift occurs for the TM mode for upœ 6 u 6 uc . (See problem 26.) As noted earlier, the frequency difference between modes is nfsr = c>2d so that the recurrence time for the pulses is the round-trip cavity time 2d/c. Typically, such absorption bands lie in the ultraviolet, above optical frequencies, so that the material is transparent to visible light. Then f2 = - a 1.33 b1- 35.742 = 47.53 cm 1 to the right of the second principal plane, and r = 1.52 - 1.33 1 - 35.742142 = 0.715 cm 11.5221 - 252 s = - 1.52 - 1 147.532142 = - 2.60 cm 11.5221 + 252 Thus the principal point H1 is situated 0.715 cm to the right of the left vertex of the lens, and H2 is situated 2.60 cm to the left of the right vertex V2 . Show that the ratio of the radii observed for a particular order fringe is very nearly the square root of the liquid's refractive index. The mathematical argument departs from that for the single slit with Eq. (4). In third-order theory, the Petzval surface is always situated three times farther from the T surface than from the S surface and always lies on the side of the S surface opposite to that of the T surface. If the first zone is subdivided into smaller segments, which advance by equal phases, the corresponding subzone phasors can be represented by b1 , b2 , Á , as shown. The small coherence length associated with the phase mismatch in many crystals (see Example 2) makes the construction of a QPM crystal by the method just described somewhat impractical. (b) Refraction in the 180° meridian yields +2.00 D of hyperopia. As a result, a negative sign between the two terms on the right of Eq. (17) would have been an appropriate choice. Recall that a complex quantity can be represented as a vector in a phasor diagram in which the real and imaginary parts of the complex quantity are, respectively, the horizontal and vertical components of its vector representation. The solid angle dv1 = dA2 cos u2>r2, where dA2 cos u2 represents the projection of area dA2 normal to the central ray. Then, find the amplitude of the light transmitted by the developed film when irradiated by the reference beam. Radiometric quantities are related to photometric quantities through the luminous efficiency curve of Figure 2 in the following way: Corresponding to a radiant flux of 1 W at the peak wavelength of 555 nm, where the luminous efficiency is a maximum, the luminous flux is defined to be 685 lm. Palais, Fiber Optic Communications (Englewood Cliffs, N.J.: Prentice-Hall, 1988). The rays all pass through a thin annular region of the lens, centered about the optical axis. In Figure 2a, a section of a wave with amplitude A is shown at a fixed time, as in a snapshot; in Figure 2b, the time variations of the wave are pictured at a fixed point x along the wave. Therefore, the images of these sources formed by lenses and mirrors have finite sizes governed by the laws of geometrical optics. New York: American Elsevier Publishing Company, 1969. Here, the limits of integration covering the apertures of the two slits become those indicated in Figure 13. In other, more complex forms, referred to as higher-order modes or Hermite-Gaussians, the electric field takes on transverse irradiance distributions that depart from the simple Gaussian variation and exhibit an ordered pattern of "hot spots." In many cases, the output laser beam consists of a mixture of modes: the fundamental and several higher-order modes. Thus, for two cases, m = 0 and m = 1, Figure 15 shows separate sketches for Hm1xs2, for Hm1xs2exp1 - xs2>22, and, finally, for [Hm1xs2exp1- xs2>22]2, the sketch that gives direct evidence of the burn pattern to be expected.9 After studying Figure 15, we see that the irradiance variation has m zeros along the x-axis, discounting the zeros at the distant tails of the Gaussian envelope. The result2 is expressed by y c l¿ = y l 1 + c a 1 - (44) where l¿ is the Doppler-shifted wavelength and y is the relative velocity between source and observer. What must be the population inversion in the gain medium to produce a small-signal gain coefficient (at linecenter, n¿ = n0) of 0.03/cm? The geometrical relationship of sides is equivalent to the Bragg diffraction condition. A technique like this was used to remove a sawtooth pattern from the video micrograph of a diatom frustule, as shown in Figure 6. Of course, each of these half-period, or Fresnel, zones could be subdivided further into smaller parts–subzones– for which the phase varies from one end of the zone to the other by p. Takara, "Effects of Dopants on Transmission Loss of Low-OH-Content Optical Fibers," Electronics Letters, Vol. 15 What theoretical ratio of high-to-low refractive indices is needed to give at least 90% reflectance in a high-reflectance stack of two double layers of quarter-wave layers at normal incidence? The transmitted portion of the beam undergoes an internal Film Substrate n1 ns n0 t B z x Er1 E Ei1 Er 2 E B B E ut2 E E ut1 y u0 B E0 E B u0 B Et1 (a) Ei2 Et2 (b) Figure 1 Reflection of a beam from a single layer. Points O and I are conjugate points with distances s and s¿ from the surface vertex at V. Since each pair constitutes similar triangles, we may set up proportions between sides that represent the lateral magnification: f hi = x ho hi x¿ = ho f and Introducing a negative sign for the magnification, due to the inverted image, m = - f x¿ = x f (35) The two parts of Eq. (35) also constitute the Newtonian form of the thin-lens equation, xx¿ = f2 (36) This equation is somewhat simpler than Eq. (29) and is found to be more convenient in certain applications. Figure 6b shows that the hyperopic eye must (and can) accommodate to see distant objects clearly. These interruptions introduce additional Fourier components into the spectrum of the oscillations of the gain medium and hence contribute to the broadening of the atomic response. 7 A point source of monochromatic light (500 nm) is 50 cm from an aperture plane. Later we shall show that 2I0 is the irradiance at P that results for an unobstructed wavefront—that is, for "diffraction" through an aperture of infinite extent. Absorption in the infrared is due to molecular vibrational bands. (27) and (28), we have for metals, TE: TM: ' Er cos u - 2n 2 - sin2 u = ' E cos u + 2n 2 - sin2 u (63) ' ' Er - n 2 cos u + 2n 2 - sin2 u = ' ' E n 2 cos u + 2n 2 - sin2 u (64) ' Introducing n as nR + inI into Eqs. To reconstruct the image of the scene, the hologram is situated in the reference beam again, as in the formation of the hologram (Figure 2b). Such structures possess a single optic axis and are called uniaxial birefringent. The separated line images T and S are revealed as sections of the beam by fluorescent screens. a wave as a simple plane wave is a useful approximation if a portion of the wave has nearly planar wavefronts over the region of interest. This rotational symmetry simplifies the analysis of the imaging properties of such a spherical lens. At this point, each of the original zones, as in Figure 7 for example, now contain two half-period zones. First we examine the structure and functions of the eye. In 16a, the laser medium is shown situated between the mirrors of the optical resonator. As discussed previously, the useful order of diffraction is large and the spectral free range is small, so that a second concave grating is used to disperse the overlapping orders in a direction perpendicular to the dispersion of the echelle grating. Complementary apertures introduced into such systems then give, outside the central image, identical diffraction patterns. A plot of transmittance T versus round-trip phase difference d for selected values of reflection coefficient r. For example, if 2nt = l0 , the wavelength of the light in vacuum, the two interfering beams, on the basis of optical-path difference alone, would be in phase and produce constructive interference. Figure 20b shows 0 0.05 0.1 0.15 0.2 0.25 0.3 0.35 0.4 0.03 0.04 0.05 0.06 Change in cavity length (mm) Change in cavity length (mm) (a) (b) Figure 20 Problem 21. In this case, the scattering centers (particles) are arranged—more or less—in an orderly fashion so that oscillators that are closer together than a wavelength of the incident light become coherent scatterers. Determine the diameter for single-mode performance and the number of propagating modes when d = 50 mm. When the wave character of the light may not be so ignored, the field is known as physical optics. Optically active materials modify the state of polarization of a beam of polarized light and can be represented mathematically by a Jones rotator matrix. As a consequence, and as illustrated schematically in Figure 5c, the uncorrected myopic eye forms a sharp image of distant objects in front of the retina, and, of course, a blurred image results at the retina. With a transmission function EA1x, y2 in its first focal plane, the Fraunhofer diffraction pattern A P1kX , kY2, which is its Fourier transform, is produced in the second focal plane, the spectrum, or output, plane. We shall see that R is the radius of curvature of the wavefront and w is related to the transverse dimension of the beam. If the spectral exitance of Eq. (5) is integrated over all wavelengths, the total radiant exitance or area Spectral radiant exitance (W/m2 mm) 10E7 6000 5E7 5000 4000 3000 1.0 Wavelength (mm) 2.0 Figure 3 Blackbody radiation spectral distribution at four Kelvin temperatures. The curves cross at v = 1v2p - g221>2, as is evident from Eq. (64). Returning to Eq. (61), we find, as before, two equations from which the real and imaginary parts of the refractive index can be calculated. According to Huygens, the remainder of each wavelet is to be disregarded in the application of the principle. Find the diameter of the image of the moon viewed through the telescope at near point of 25 cm. 2 PHOTOMETRY You should be familiar with the terms and definitions associated with radiometry, which applies to the measurement of all radiant energy. Experimentally, one finds that a separation of 1 mm at a distance of about 2 m is just barely resolvable, giving 1¢u2min = 50 * 10-5 rad, about 1.5 times the theoretical limit. Thus, for m = 1, there is a single zero at xs = 0 and peaks on either side. Again in 1922, the model of light quanta came to the rescue for Arthur Compton, who explained the scattering of X-rays from electrons as particle-like collisions between light quanta and electrons in which both energy and momentum were conserved. In the case of normal incidence, the reflection coefficient (or ratio of reflected to incident electric field amplitudes) is given by r = 1 - n 1 + n (27) 177 Interference of Light where the relative index n = n2>n1 . 550 nm Aperture Photocell 3 mm Plane waves Figure 19 3 A distant source of sodium light (589.3 nm) illuminates a circular hole. Assuming they are halfway: a. 6 IMAGING BY AN OPTICAL SYSTEM We discuss now what is meant by an image in general and indicate the practical and theoretical factors that render an image less than perfect. Of course, there is no absorption stimulated by the electromagnetic vacuum because the vacuum, being the ground state of the electromagnetic field, can provide no energy quanta to the atom. (b) Energy level diagram for the helium-neon laser, showing the production of the 0.6328-mm laser line in terms of the four steps (circled numbers) outlined in (a). By light modulation, we mean the modification of the amplitude (AM), frequency (FM), phase, polarization, or direction of a light wave. In this way, we account for multiple beams in the interference. The energy in each cycle is the energy contained in a single pulse: Ep = Pp ¢tp a. According to this discussion, when B = 0, the output plane is the image plane, so that the image distance x is determined by setting 16 - 2x = 0 3 or x = 24 cm Further, the linear magnification m is then given by the value of element A: m = A = 1 - Input plane Output plane R 4 cm 16 n 1.0 n 1.50 x = -1 12 x Figure 10 Schematic defining an example for ray-transfer matrix methods. Chapter 15 Chapter 18 1. Since the film plane is fixed, a focused image is procured by allowing the lens to be moved farther from the film, that is, by "focusing" the camera. E Free electron continuum 0 E4 0.85 eV E3 1.51 eV E2 3.4 eV E1 13.6 eV Figure 1 Allowed energies of the electron in the hydrogen atom. The lasing levels in the Ar+ laser are two different electronic 576 Chapter 26 Laser Operation energy states of a singly ionized argon atom. In others, excitation occurs by means of inelastic atom-atom (or molecule-molecule) collisions. Light rays from an object are admitted into a light-tight box and onto a photographic film through a tiny pinhole, which may be provided with any simple means of shuttering, such as a piece of black tape. To be more specific, when cos d = + 1, constructive interference yields the maximum irradiance Imax = I1 + I2 + 2 2I1I2 (15) This condition occurs whenever the phase difference d = 2mp, where m is any integer or zero. Minimum deviation occurs for an angle of 23°. This treatment is strictly valid for cases where the individual E vectors are parallel; it is often applied in cases where they are nearly parallel. Interference effectively occurs between the two coherent virtual images S1 and S2 , acting as sources. Pedrotti, and Peter Bandettini. 1 (Reading, Mass.: Addison-Wesley Publishing Company, 1963), Ch. 32, 33. A wide range of spectral outputs is possible by using different materials in the core of the carbon rod. In a system like that of Figure 1a, a screen held at the position of the exit pupil receives a sharp image of the circular opening of the aperture stop. Thus we can write, EA = a a ES ikr¿ be r¿ (4) where a is a proportionality constant with dimensions of inverse length. "Light." In Lasers and Light, pp. Calculate the beam spot size w at the entrance and exit faces of the beam expander. The Diffraction Grating 14 A reflection grating, ruled over a 15-cm width, is to be blazed for use at 2000 Å in the vacuum ultraviolet. + + + 1t + t2 = E01 1t2 K E01 . Geometric Optics: An Introduction. Exit Window (E xW) The exit window is the image of the field stop formed by all optical elements following it. (b) Piezoelectric spacer used to control the mirror separation d. Let the light incident on such a zone plate consist of plane wavefronts. This is descriptively called pincushion distortion. However, we intend to ' describe fields E whose primary dependence on z is described by the rapidly varying factor eikz. In Figure 1 two wavefronts are shown emerging from an optical system. The incident light beam with wave vectorBk can be considered a flux of photons, each of energy Uv and momentum Uk, where v is the angular frequency and U is the Planck constant divided by 2p. This ordering of fringes may be inverted for convenience by associating another integer p with each fringe of order m, where p = mmax - m = 2d - m l m 99 p1 (6) m 98 p2 Using Eq. (6) to replace m in Eq. (4), we arrive at pl = 2d11 - cos u2 p = 0, 1, 2, A dark fringes m 97 p3 (7) where now the central fringe is of order zero and the neighboring fringes increase in order, outward from the center. (New York: Holt, Rinehart and Winston, 1985), Ch. 8. Without a focusing device, these virtual fringes do not appear. Glass fibers are therefore preferable in long-distance applications. In such a representation, the length of the vector is the magnitude of the complex quantity and the angle that the vector makes with the horizontal axis is the phase of the complex quantity. (a) zFF ≫ 1.46 m (b) 0.371 mrad (c) win = 1.113 cm; wout = 11.13 cm (d) z2 ≅ 0.1 m; w02 ≅ 1.81 × 10−7 m 16. What frequencies are radiated by the polarization wave? The two parallel beams leaving the film at A and C can be brought together by a converging lens, the eye, for example. 31 1941; 488. Example 1 a. This illustrates how the system matrix can be used to find image locations and sizes, although this may usually be done more quickly by using the Gaussian image formulas derived earlier. To correct for myopia, tissue in the center of the cornea is removed in order to effectively flatten the cornea and reduce the refractive power of the eye—allowing the relaxed eye to form images of faraway objects on the retina. Nonlinear Optics and the Modulation of Light degenerate four-wave mixing, illustrated in Figure 15, can be used to produce the phase conjugate beam. Solution At 0.82 mm, Figure 13 gives a value of near 100 ps/nm-km. The total field in the cavity is a superposition of these fields with frequencies corresponding to the cavity-mode frequencies that are separated by the cavity free spectral range c/2d, where d is the cavity length. The dispersing powers of the components are, through appropriate selection of glasses, in inverse proportion to their powers. Variations in temperature produce variations in optical-path length by changing the refractive index of the air. This occurs at the critical angle, wm = wc . Note that refraction by the eye lens is not shown. Thus by B Eqs. Note that a = 0 when p = 0 and a = p when p = N = 8. Convert the result to an image distance in centimeters. As the seed photons pass by the atoms in the upper laser level, stimulated emission adds identical photons in the same direction, providing an increasing population of coherent photons that bounce back and forth between the mirrors. Sketch this pulse. Assume an average wavelength of 700 nm for the sun's radiation that reaches the earth. Two such technologies are discussed below. A difference or idler frequency v3 = vi = vp - vs can be produced. These are periodic waves, representing smooth patterns that repeat themselves endlessly. That is, the phase shifts upon reflection from opposite sides of the beam splitter differ by p. The extraordinary ray is not B perpendicular to the plane wavefront; rather, the ray direction along S is from the wavelet origin O to the point of tangency of the elliptical wavelet with the plane wavefront. For large N, its principal maxima are bright, distinct, and spatially well separated. Thus, by using prisms with apex angles intermediate between these values, the perpendicular component can be totally internally reflected while the parallel component is transmitted. If the small-signal gain coefficient is twice the threshold value, find the irradiance of the laser output field. where the wavelength l is in centimeters. Light polarized along the same direction as 1 the TA is represented by the Jones vector c d , and light with a polarization 1 y x Rotator u z Figure 10 Operation of a rotator. 1 Figure 3 Scaled population densities of the excited (2) and ground (1) states of a twolevel atomic system as a function of the scaled irradiance I>1A 21hn¿>s2. Because of interference, a broadcast "beam" is limited by interference minima. Since these perpendicular fans of rays focus at different distances from the lens, the two images are line images, shown as T and S for the tangential and sagittal fans, respectively. In the figure, the electric field E, made up of equal parts along the x- and y-directions, oscillates along a line making an angle of 45° with the x-axis. The result is the generation of incoherent light. 6 Consider a Soleil-Babinet compensator, as shown in Figure 11. Birefringence in Optical Fibers You should be familiar with some of the advantages of single-mode optical fibers. The intersection of the two reflected rays occurs behind the mirror and locates a virtual image of dimension hi there. Waveguide dispersion, on the other hand, is always positive. 12 Light of wavelength 485 nm is incident normally on a screen. Distances to the left of the vertex V are negative, and to the right, positive. For observation points P¿ at very large values of y in Figure 14a, the irradiance approaches the value Iu for the unobstructed wavefront. Unlike two-dimensional holograms, volume holograms can reproduce images in their original colors when illuminated with white light. Verrier. Then the light reaching any point such as P on the screen is due to parallel rays of light from different portions of the wavefront at the slit (dashed line). If the frequency-sensitive position of the output beam is detected by a photodetector array, the AO device can be used as a spectrum analyzer. Examine element B to determine the general relationship between object and image distances for the lens. With the help of Eq. (64), we can form the factor eip1z2 as eip1z2 = w0 -i1m + n + 12arctan1lz>pw022 w0 -i1m + n + 12arctan1z>z02 e = e w1z2 w1z2 (65) where we have used Eqs. Repeated reentries of the beam into the laser cavity initiates stimulated emission that produces the laser pulse. For the present, we call this factor F1u2, a function of the angle u between the directions of the radiation incident and diffracted at the aperture point O. Find the temperature at which the ratio of the likelihoods P2>P1 is 1/1000. Note carefully that the values for the refractive 22.38 mm 20 mm 2.38 mm 1.96 mm 15 mm 7.38 mm N H H S1 F S2 AC Figure 3 Representation of H. +20 and −20 cm 18. From Eq. (33), we conclude that r = + 3.125 cm and s = - 2.083 cm. 11 A pinhole of diameter 0.5 mm is used in front of a sodium lamp (5890 Å) as a source in a Young interference experiment. Thus, Eq. (52) can be satisfied for all x, y at arbitrary z only if (1) the g-expression equals a constant, say -C1 , (2) the h-expression equals a constant, say - C2 , thereby (3) leaving the third term equal to C1 + C2 . 4, 5. Extinction of the reflected light is observed to occur at wavelengths of 525 and 675 nm in the visible spectrum. Ch. 1. With these definitions, Eq. (31) may be written V + V¿ = P (32) I 2F O F 2F F s s (a) 3F O I s s (b) Figure 25 Change in curvature of wavefronts on refraction by a thin lens. One such transition, leading to the 1.1523 mm line, is indicated in the figure. The low-pressure mercury discharge tube is often used to provide, with the help of isolating filters, strong monochromatic radiation at wavelengths of 404.7 and 435.8 nm (violet), 546.1 nm (green), and 577.0 and 579.1 nm (yellow). A side view, which shows the curvature of the cylindrical wavefront, is drawn in Figure 11b. When the incident and diffracted rays are on the same side of the grating normal, as they are in Figure 1, um is considered positive. Each diffraction spot in the spectrum plane, with coordinates (X, Y), represents spatial frequencies present in the aperture function, as we have pointed out. electrons in the atom. Among the extrinsic losses are inhomogeneities and geometric effects. 22 Trace a ray originating 7 mm below the optical axis and 100 mm distant from a doublet. New York: Holt, Rinehart and Winston, 1970. From Figure 3b, the components of the resultant phasor E0eia are E02 sin a2 E02 E0 E01 sin a1 a1 E01 cos a1 E02 cos a2 (b) Figure 3 Phasor diagrams useful for determining the sum of two harmonic waves. The hologram acts as a matched filter, recognizing and transmitting only that spatial spectrum similar to the one recorded on it. IEEE, Vol. . Now ¢w = 12p>l02L¢n, where l0 is the vacuum wavelength and L¢n represents the optical-path difference induced in each component by the applied field. Chapter 23 Dichtburn, R. The two types of photoreceptors, rods and cones, differ in shape, number, location, and function. Thus, the ray equations, Eq. (22), become for this ray yf = Ay0 + Ba0 and 0 = Cy0 + Da0 or y0 = - a D ba C 0 (23) For small angles, Figure 12a shows that a0 = Input plane H1 Output plane PP2 PP1 F1 y0 -p N1 H2 N2 F2 Optical system r Figure 11 Location designations for the six cardinal points of an optical system. The example illustrates a one-dimensional correlation. On the other hand, when we are looking at the sunlight "head-on" at sunrise or sunset, after it has passed through a good deal of atmosphere, we see reddish or yellowish light, that is, white light from which the blues have been preferentially removed by scattering. Sketch the chief ray and the two extreme rays through the optical system, from the top of the object to its conjugate image point. Use the matrix method to support your answer. A Snellen fraction of 20/300 means that the test subject sees poorly, reading at a distance of 20 feet what the normal eye reads as well at a distance of 300 ft. That is, Pdet = P1 + P2 + 22P1P2 cos d 2 A. Second Harmonic Generation Second harmonic generation results from the contribution of the secondorder term in Eq. (3): P2 = e0x2E 2 (4) in which the second-order polarization term P2 of the optical medium is proportional to the square of the electric field. An empirical relation that approximates the curve, introduced by Augustin Cauchy, is nl = A + B C + 4 + Á 2 l l 200 1600 l (nm) Red Green Violet White Figure 12 Typical normal dispersion curve and consequent color separation for white light refracted through a prism. Calculate its magnifying power when viewing an image at infinity. (15) and (16), the coherence length is lt = c ¢n The frequency band ¢n can be related to the line width ¢l by taking the differential of the relation n = c>l. We have shown earlier that this D z0 Rayleigh range 3(2w0 (2w0 2w0 Waist Laser w0 Figure 11 A collimated laser beam and the corresponding Rayleigh range z0 . In a Littrow mount, the grating returns, along the incidence direction, light of wavelength l = 211>792sin163.432 2a sin ub mm = 755 nm = 30 30 The total number of lines on the grating is N = 179216102 = 48,190 so that the resolving power is P = mN = 1302148,1902 = 1,445,700 at the blaze wavelength of 755 nm. The last of these, C1G2, is called the optical transfer function (OTF), because it transfers or changes the object spectrum into the image spectrum. Mathematically, the power expansions for the sine and cosine functions, given by sx - x ~ x3 x3 + A 3! 5! cos x = 1 - x4 x2 + A 2! 4! were developed by using Taylor's series. Eqs. (4)-(8) hold in a reference frame moving with the atoms. Although a quadratic mean is not the same as an arithmetic mean, it is the standard that is used in practice. This section is a study of the propagation of light through a medium which is a one-dimensional array of thin first forms. The FWHM, 2e1 + 2e2, of a transmittance peak. (a) 83.3 cm (b) 83.3 fringes (c) 150 nm 556 nm, 415 nm 20.3 0' 5" 35.60" 9.09 × 10−5 cm; orders 4 and 3, respectively 498 nm 1.35; 103 nm (a) 2.78% (b) 89.3 m (c) 1% Stops film becomes wedge-shaped under gravity; the angle of the wedge is 1'14" 15 1.16 × 10−3 cm 1.109 nm; 184 3m 603.5 nm; 23.9 mm; 2.87 × 10−4 cm 928 nm (a) 980 V/m (b) 30° (c) r = 0.28; tf = 0.9216 (d) 274, 253, 19.8 V/m; 7.8%, 6.7%, 0.041% (e) 903, 70.8 V/m; 85%, 0.52% (f) 258 nm 4. Such correlation is applied, for example, in the problem of pattern recognition. The content of Eq. (13) implies, for example, that if the hologram were made with coherent X-rays and viewed with visible light, magnifications as large as 106 could be achieved without deterioration in resolution. In this section we derive steady-state population densities for a two-level atomic system, in which the lower energy level is the ground state of the system. Since the axis of any bundle may be considered an optical axis, there are no off-axis points and thus coma and astigmatism do not enter into the aberrations of the system. The numerator is identically zero under the condition a = p/N, where p takes on integer values. However, this path difference 270 Chapter 11 Fraunhofer Diffraction e cannot be ignored in the phase factor. Today, with the help of computers, the necessary calculations yielding the progressive changes in a ray's altitude and angle is done more easily and quickly. One of the mirrors is chosen with a reflectivity as close to 100% as possible. To apply Rayleigh's criterion. the optical system may be unequally spaced. The full details of aberration theory are too formidable to treat in this chapter. In either case, when e = ml, all diffracted waves are in phase and the grating equation becomes a1sin ui + sin um2 = ml, m = 0, , 1, , 2, A (2) When it is not necessary to distinguish between angles, the subscript on the angle of diffraction, um, is often dropped. As noted in Figure 1, the eye is covered with a tough white coating, the sclera, that forms the supporting framework of the eye. f1z, t2 = A exp1ikz2 + B2ex2 - 2B1z2 9 A harmonic wave traveling in the +x-direction has, at t = 0, a displacement of 13 units at x = 0 and a displacement of - 7.5 units at x = 3l>4. Recall that the resolving power P is defined in general by P K l 1c1lmin (8) In the present context, 1c1lmin is the minimum wavelength interval of two spectral components that are just resolvable by Rayleigh's criterion. In a transmission grating, light is periodically transmitted by the clear sections of a glass blank, into which grooves serving as scattering centers have been cut. Nave New York: John Wiley & Sons, Inc., 1991. The Paschen-Runge design, Figure 11, makes use of the Rowland circle. The constructions shown in Figure 4a and 4b suggest that "stopping down" the optical system, so that only nearly paraxial rays get through the entrance pupil, will limit the effect of spherical aberration. Scaled population density N1/NT 0.5 N2 /NT 0 Nm /NT ac0.5 g=1 0 2 4 6 Scaled irradiance Ii 10 555 Laser Operation Absorption Coefficient and Beer's Law This far we have concentrated on the change in population density induced by an incident electromagnetic field. The more convenient angular magnification is clearly a measure of the image size formed on the retina and is used to describe the magnification when eyepieces are involved, as in microscopes and telescopes. PROBLEMS 1 Use Eq. A 1 = 11 + R 2 221112 cos e Mutually coherent beams for the unpolarized two beams to show that the irradiance pattern of a Gabor zone plate (the hologram of a point object) is given approximately by Plane waves I1 Subject beam I2 I2 I = A + B cos21ar22 where A = 11 + 12 - 2211I2 , B = 4 2211I2 , and a = p> 12d2. We examine a few special cases next. (1) and (2) can be approximated as, q RSt.Em. = B21N2g1n2 n1 - 1 211 / mq1 2 do m n1 E 21N2g1n2b0 = B21N2g1n21>2 0 (10) and q RSt.Abs. Orders are shown at different distances from the lens for clarity. 568 Chapter 26 Laser Operation states that, The coefficients of 1r220 and 1r221, when set equal to zero, yield (b) r = q (1 - r 1 f) (a) (1) Equations (13) can be integrated to give q1z2 = q1z2 = q1o2 + z Now, q(z) is, in general, a complex function. A similar analysis (see problem 6) can be used to show that rTM , like rTE , has unit magnitude when the angle of incidence exceeds the critical angle and enables one to find the phase shift on total internal reflection fTM for the TM case. According to Eq. (50), the thinning broadening contribution esH,t to gh the linewidth is csH,t = nfsr 1 1 1 1 1 + a h + a h Hz t2 tp t1 2p 10 * 10-6 0.1 * 106 s -1 * 106 Hz n0 (a) 5. What is the beam divergence angle of this laser? 3 17 Show that the matrix c 1 1 d represents a right-circular -1 polarizer, converting any incident polarized light into right circularly-polarized light. Fiber Optics 261 wavelength-division multiplexing (WDM), along the + z-axis n. We conclude that the irradiance of 100 coherent ideal sources, for example, is 100 times greater than the mean total power of 100 random sources. Figure 6 shows the progress of a single ray through an arbitrary optical system. The intrinsic laser is a type of high-electric field, and carriers produced by light absorption in this region are quickly swept away to the heavily doped regions. Find the ratio of the likelihood P2 that a hydrogen atom will be in one of its excited states with energy E2 to the likelihood P1 that a hydrogen atom will be in its ground state of energy E1 if the atoms are in thermal equilibrium at room temperature (293 K). The quantity N2 representing the pulse broadening (ps) per unit of spectral width (nm) per unit of fiber length (km), is plotted against the wavelength. For the scanning Fabry-Perot interferometer, we see that large values occur when the mode linewidth is large and for large values of the finesse, which occurs for reflection coefficients close to unity. The dashed profiles represent the waveforms in the cavity. 2 Determine the limit to the number of TV station channels that could transmit on a single optical beam of 1.55 mm wavelength if a. Information obtained from interferometers at widely separated locations will aid in distinguishing signals caused by gravitational waves from those caused by local environmental and instrument noise. Note that a sphere power correction of + 2.00 D is needed to correct for the hyperopia, and a cylinder power correction of + 1.50 D is needed along the vertical meridian f = 180o2 to equalize the refractive power in the two orthogonal meridians. Find the resolving power of the grating under these conditions. The grating can be produced with a standard blaze at 630 nm for use in a Littrow mount. Axial points include focal points (F), vertices (V), principal points (H), and nodal points (N). Suppose, then, that a small signal wave at vs = v1 and a powerful pump wave at vp = v2 interact within a nonlinear medium. Wrapped, (h), the rounding of the interface of the phase, (a) Maxwell's equations,: What is the illuminance produced at ambient point on the floor, 3 m distant from P? The electric field of Eq. (43) is said to be linearly polarized along the x-direction since the direction of the electric field is always along the x-direction. Express the bandwidth of this transition as a wavelength spread given that the light resonant with this transition has a wavelength of 10.6 mm. Figure 9a illustrates the diffraction of two point objects S1 and S2 formed S1 u s S2 (a) (b) (c) Figure 9) (a) Diffraction-limited images of two point objects formed by a lens. What is the responsivity in A/W (at this wavelength) of this detector? (a) Tungsten lamp. Transmittance (%) Nonlinear Optics and the Modulation of Light 521 100 50 P Transmitted intensity VQW VHW Applied voltage V p/2 p Phase difference Modulating voltage sudden dumping of the energy stored in a laser. These perpendicular E-field components set the electronic oscillators of a scattering center into forced vibrations along the y- and z-directions. Newton maintained his basic particle hypothesis, however, and explained the phenomenon by endowing the particles themselves with what he called "fits of easy reflection and easy transmission," a kind of periodic motion due to the attractive and repulsive forces imposed by material obstacles. 8 Determine the longitudinal and lateral spherical ray aberration for a thin lens of n = 1.50, r1 = + 10 cm, and r2 = - 10 cm due to rays parallel to the axis and through a zone of radius h = 1 cm. Finally, since every optical system intercepts only a portion of the wavefront emerging from the object, the image cannot be perfectly sharp. The movable slits were therefore arranged as in Figure 15a, using mirrors that direct widely separated portions of the radiation wavefront into a double-slit-telescope instrument. In this chapter we extend our discussion of the properties and production of polarized light. The linear dimensions of the diffraction pattern thus increase uniformly with distance. In this case the optical system may be reduced to a single ray through an arbitrary optical system. To see why this is true, let us calculate the effect on the measured (a) Draw a ray diagram, (b) What we determine the constant of the and if the image is 50 cm from the given wavelength: ...

cases that are of particular interest. 1. After cancellation of the constant 1e0m0 and some simplification, we find r = n11n0 - ns2cos d + i1n0ns - n212sin d n11n0 + ns2cos d + i1n0ns + n212sin d (40) 482 Chapter 22 Theory of Multilayer Films The reflectance R, which determines the reflected irradiance, is defined by R = frf2 (41) To calculate R, first notice that the reflection coefficient r is complex and that it has the general form r = A + iB C + iD so that f r f 2 = r* = a A2 + B2 A + iB A - iB ba b = 2 C + iD C - iD C + D2 By inspection then, we may write R = n211n0 n211n0 nonsos2 cos2 d + 1n0ns - n212sin2 d (42) + ns2cos2 d + 1n0ns + n212sin2 d Example 1 A 400-Å-thick film of ZrO2 1n = 2.102 is deposited on glass 1n = 1.502. 12 CYLINDRICAL LENSES Spherical lenses and mirrors with circular cross sections are far more common in optical systems than are cylindrical lenses. This is the monomode (or single-mode) fiber. (When an aperture through which a laser beam is focused, the wave front leaving the aperture and the whole beam begins to spread out in a characteristic diffraction pattern.) When a light ray traverses an optical system consisting of several homogeneous media in sequence, the optical path is a sequence of straight-line segments. If the actual length of the cell is accurately known to be L, the change in optical path is given by cd = nL - L = L1n - 12 (9) and using Eq. (8), it follows that the index can be determined from n - 1 = a l b cm 2L (10) Consider another direct application of the Michelson interferometer, the determination of wavelength difference between two closely spaced components of a spectral "line," I and I2. New York: Academic Press, 1978. As it moves, the pulse maintains its shape. Naturally occurring calcite crystals are found in rhombohedron as a result of their crystallization into the trigonal lattice structures. Once the AS is identified, it is imaged through the optical elements to its right to find the exit pupil. Notice that the dipole oscillators (located within a narrow wavelength compound along the direction of the reflected beam. As indicated in the figure, carrier signals of different wavelengths originating from different transmitters are combined by a multiplexer into a single optical fiber. When interest lies primarily in the effects of enhancement or diminution of light waves, due precisely to their superposition, these effects are usually said to be due to the interference of light. Concepts of Classical Optics. If the wavelength separation is too large, the transmittance peak associated with the mode number m + 1 will overlap the transmission peak associated with mode number m. The chief ray, or principal, ray is a ray from an object point that passes through the axial point, in the plane of the entrance pupil. What is the far-field beam-divergence angle uFF for this laser? (d) Diffraction pattern due to a double-slit aperture, with each slit of width b like the one that produced (c), but with a/b unspecified. In practice, one often follows the evolution of a cavity photon number density by using Eqs. The condition follows from Snell's law and the geometric relationships given in the figure. (2), (3), and (4), the magnitudes of the magnetic and electric fields can also be related by E = n a bB = n a bcB (9) c v 3 TRANSFER MATRIX Our analysis is carried out in terms of the quantities defined in Figure 1. Example 3 For a straight edge, calculate the irradiance at the first maximum above the edge of the shadow. The glass rod has a refractive index of 1.60. Intermediate to the good insulator and good conductor we have treated separately are materials, like semiconductors, for which neither of these extreme cases suffice to explain the properties. Assume that the beam irradiance is constant across the focused spot. Ray aberrations are sometimes characterized by their shape and given names such as barrel distortion. The second cosine factor represents a wave with frequency vg and propagation constant kg that are much smaller than the corresponding values in the original waves are taken to be Eq. (32). 6 A Michelson interferometer is used with red light of wavelength 632.8 nm and is adjusted for a path difference of 20 mm. The speed of response is described by a time constant, a measure of the time required to regain equilibrium in output after a change in input. Typically, cos d will take on alternating maximum and minimum values, and interference fringes, spatially separated, will occur in the observation plane. 370 Chapter 15 Production of Polarized Light b. (d) Image of a square grid by a positive lens. Stimulated Absorption Stimulated absorption, or simply absorption, is the process by which the electromagnetic waves transfer energy to matter. Ellipsoid I O (b) Hyperboloid O (c) Paraboloid Figure 11 Cartesian reflecting surfaces showing conjugate object and image points. Chapter 14 Gerrard, A., and J. Determine the visibility of the fringes on a screen 1 m away, in the vicinity of the fringe of order m = 20. On reconstruction, each scene appears in its own light when viewed along the direction of the original scene, without mutual interference. Interference fringes produced by light reflected from the film surface and substrate allow a determination of the film thickness d. For each of the two components of polarized light, Fresnel developed the Fresnel equations, which give the amplitude of light reflected and transmitted at a plane interface separating two optical media. From our knowledge of Fourier series, we conclude that the finer features of the image disappear when spots corresponding to the higher spatial frequencies are blocked. 4 INTERFERENCE IN DIELECTRIC FILMS The familiar appearance of colors on the surface of oily water and soap films and the beautiful iridescence often seen in mother-of-pearl, peacock feathers, and butterfly wings are associated with the interference of light in single or multiple thin surface layers of transparent material. Shield Output mirror Ruby rod Beam direction End mirror Flashlamp Power supply The Gain Medium Laser systems are typically named by the makeup of the gain medium used in the device. Consider a ray with parameters 1y1, a12 incident on the entrance plane of an arbitrary optical system described by the overall system matrix of Figure 4. Now, with this definition, the ratio equations can be written as dN2 s1 = - A21N2 (19) dt and N1 = a1 = 1 - N1 12 dt ms 2 (15) and Now s has a dimension of area which accounts for its designation as a cross section. In the ordinary case of a lens in air, with n = n_i = 1, notice that r = y and s = w. First and second principal points are superimposed over corresponding nodal points. The fractional power f fmc = f1r = a2> t Dot passing through a circular aperture of radius a, has the form E fmc = E fmc E1r = a2 I = 4 (ot £ tot 1w2Dv·n21z220 = 1 ns 2 ot e 1z2 1 ka Aperture 12pr dr2 -2r2>w2 0 Carrying out the integration and using the result just found for £ tot, we find f fmc = 1 - e-2a >w 2 2 Figure 12 shows the fractional power that passes through a circular aperture of radius a, versus the ratio a/w, where w is the 100% Aperture geometry 99% 86% w = a' a) tot 50% aw a 1.5 w a Transverse Gaussian irradiance of beam entering aperture Normalized aperture radius a/w Figure 12 Fractional power transmission of a Gaussian beam of spot size w through a circular aperture of radius a. 26, 27. In this case, we find ID IC IF f1 f2 f. 3653 cm 0.3961 cm 0.2966 cm -11.0575 cm - 11.0575 cm -10.8485 cm 15.0000 cm 15.000 cm 15.007 cm (b IR IF IB (a) (d) 0 = (1n - 12 1K1 + K2 2 - 1n - 12 2K1K2 2 = 0 (d) Performing the differentiation and canceling the 0, there remains f1 = f2 2 28. 3B IR For a thin lens, achromatizing condenses focal lengths (nearly equal), eliminating longitudinal and lateral aberration at the same time. When we speak of linear optics, we assume that an optical disturbance propagating through an optical medium can be described by a linear wave equation. Consider next the lightBendering the crystal from the left. Presbyopia As mentioned in the preceding section, human eyes lose ability to accommodate with age. When illuminated with sodium light (589.3 nm), fringes appear on the screen with a spacing of 0.5 mm. The aberration function a12 for the point Q on the wavefront may be expressed as a12 = ... (2) Let refraction occur at plane (20) we relate the elevation of the ray PQPc to the axis PBPc and consider points B, O, and Q to lie in a vertical plane approximating the wavefront at O. In these inelastic interactions, the collisions induce a change in the internal state of one or both of the atoms participating in the collisions. 17 Calculate the focal length of a thin meniscus lens whose spherical surfaces have radii of curvature of magnitude 5 and 10 cm. Overall, the eye can be represented approximately as a thin, positive lens of focal length equal to 17 mm in the relaxed state (distant vision) or 14 mm in the tensed state (near vision). Two consecutive internal reflections thus produce a relative phase shift of 21 - 3p>4 = - 3p>2 equivalently, +p>2 between the perpendicular components of the E-field. In the far field 1z W z02, the phase fronts again become planar. 100 mm Metal electrode p+ GaAs 10 mm n GaAs Ga1-xAlx layer n GaAlAs n GaAlAs Active region Contact Stripe geometry Figure 19 Stripe-heterojunction semiconductor laser. When their image pattern begins to overlap substantially, it becomes more difficult to discern the patterns as distinct, that is, to resolve them as belonging to distinct object points. A laser system converts pump energy (which may be electrical or optical in nature) into intense, highly directional, nearly monochromatic, electromagnetic wave energy. Determine the critical and polarizing angles. Again, we find that the propagation of the wave in a metal; (c) If the lens is to be used to produce a collimated beam, how do these answers change? For most photographic work, d is of the order of thousandths of a millimeter. Each elemental radiating area dA1 contributes to each elemental irradiated area dA2 . Values assumed are vp = 1.63 * 1016 s-1 and g = 4.1 * 1015 s-1. In this case, the waves add to form a resultant wave that has an amplitude that is (in magnitude) the difference of the amplitudes of the waves being superposed and which is in step with the individual wave of largest amplitude. Similarly, viewed from a point on the z-axis, the z-vibrations are missing, and light is linearly polarized along the y-direction. This balance is not maintained at the edge of an aperture in the screen, where the distribution of oscillators is interrupted. Consequently, infrared radiation is sometimes termed "heat radiation" and finds application in nightvision scopes that detect the IR emitted from objects in absolute "darkness" at different temperatures (and so with different peak wavelengths of emitted radiation) are imaged as areas of contrasting brightness. For a grating of 1200 grooves/mm and ui = 38°, the firstorder spectrum for wavelengths between 200 and 1200 nm falls between the angles - 22° and 56°, respectively. Thus if z = a ib, ... the asterisk is used to denote the complex conjugate. The method lends itself to computer techniques for tracing a ray through an optical system of arbitrary complexity. Proceeding with the approximate equivalent, we used a Taylor series expansion in the small quantity r2>z2. First, any Jones vector may be multiplied by a real constant, changing amplitude but not polarization mode. Ohatak, Ajoy K. = B12N1 1C 0 and q RSp 2tn. = A21N2 (3) gain (n) ytoi ytoi In the last relation we have used the fact that the lineshape function g1n2 is normalized so that its integral over all frequencies is unity. (3) and (4). "The Optical Properties of Materials." Scientific American, Sept. When the electric fields are parallel, on the other hand, the interference term makes its maximum contribution. What ratio of amplitudes produces a visibility of 0.5? 4 a. Thus linearly polarized incident light with equal TM and TE components, after two internal reflections at 53°, will be transformed into circularly polarized light. Since the sum of the light transmitted under both conditions must be all the incident light, that is, white light, it follows that the colors observed under these two transmission conditions are complementary colors. Such a series of terms is called a Fourier series. A typical CCD panel in a now-bonded package is shown in Figure 6. We have agreed to use Rayleigh's criterion, which determines the limit of resolution of the diffraction-limited line images. The result is a compound lens that has a net focal length but reduced dispersion over a significant portion of the visible spectrum. Example 2 For the He-Ne laser geometry given in Figure 10, use the ABCD propagation law to determine the spot size w0 of the external beam waist and its distance from the outer surface R3 of the mirror-lens combination. The coherence length Lt is defined by the relation cLt/C = p. Notice also that with the correcting plate attached at twice the focal length of the mirror, the telescope is twice as long as the telescopes described previously in Figure 34. The output of a Michelson spectrometer is fed to a photodetector. Thus, vertically polarized light entering the liquid crystal will emerge from the device polarized along the horizontal direction and so pass through the second horizontal polarizer. In the pumping radiation at resonance is: (40) For radiance L1 at dA1 is given by L1 = d2 £ 1 d2 £ 1 = dv1 cos u1 dA1 cos u2 14A2 cos u2>r22d4A1 cos u1 215 (19) As a similar argument, in which we reverse the roles of dA1 and dA2 in Eq. (20), an area of the surface illuminated by the source. According to Eq. (12), the radiance L1 at dA1 is given by L1 = d2 £ 1 d2 £ 1 = dv1 cos u1 dA1 cos u2 14A2 cos u2>r22d4A1 cos u1 215 (19) 4 Notice that the radiative transfer equation, the optical path length is unaffected. In the final step of the solution. Now, in a nonabsorbing medium, the power associated with the radiation passing through the continuous bundle of rays remains constant, that is, dE / 1 = dE 2 , so that we can conclude from Eqs. The effect of variations in signal strength is then to produce variations in the contrast of the interference fringes, whereas variations in phase (or direction) of the signal waves produce variations in spacing of the fringes. In general, both homogeneous and inhomogeneous broadening occur g (n) QnD (n#) n0 n Figure 11 A Doppler-broadened lineshape function g1n2 (solid curve) is shown as a function of n. The fiber couplers FC1 and FC2 function as beam splitters. The solid angle £v is equal to dAT>R2 , where (A T = pr2T = p1R tan1a>2222 M pR21a>222, since tan1a>22 M a>2 for small angles. Accordingly, the corrective contact lens should have a focal length of -100 cm. To be detected as a single pulse, the output pulse must not spread to the extent of significant overlap with neighboring pulses. Heated cathode Deflecting coil Vacuum tube Electron beam Anodes 17 Screen Deflecting coil Optical Detectors and Displays INTRODUCTION In this chapter we give a qualitative description of the more common types of optical detectors and displays. Note that the arrow in the diode symbol points from the p-side to the n-side of the diode. See problem 1. If the two patterns are identical, for example, and so situated that Aperture Spectrum Image Output S1 Figure 7 Optical correlator formed by the combination of an optical filter and a spectrum analyzer. Find the wavelengths of the four visible hydrogen photons in the Lyman series. Vent, C. Calculate the final image position relative to the last lens and its linear magnification relative to the original object when (a) all three lenses are positive, (b) the middle lens is negative, (c) the first and last lenses are negative. Both of the Stokes relations will be needed in the discussion that follows. The designation "6 * 30" for binoculars means that the angular magnification M produced is 6* and the diameter of the objective lens is 30 mm. Shlurov, and Boris Ya. Zel'dovich, "Optical Phase Conjugation," Scientific American, Dec. Thus, using Eq. (33) gives Iu = I01E212 = 1051C1 g 2 - C1 - g 22 = 151 g 2 - g1 - g 22R = 10 e 12 + 122 = 20 (37) Other irradiances may be compared conveniently to the value of Iu = 20 for the unobstructed wavefront. If the illumination is green light of 546.1 nm, what is the diameter of the "stop" in the film that caused the shift? (b) Cassegrain telescope. What magnification would result if coherent X-rays of 1 Å wavelength were usable to construct the hologram? Telescopes may also be distinguished by the erectness or inversion of the final image and by either a visual or photographic means of observation. The Michelson, Twyman-Green, and Mach-Zehnder interferometers are all two-beam interference instruments that operate by division of amplitude. This careful reconstructing of the surface is designed to correct for myopia, hyperopia, astigmatism, and combinations thereof. For example, after only six such interfaces, or three optical components in series, 93% of the incident light survives in the case of MgF2 coatings, compared with 77% in the case of uncoated glass. The component of P2 oscillating at 2v corresponds to dipole oscillations in the medium at this same frequency. T E B AR A1 A2 b2 b1 0 Reference direction Figure 10 Phasor diagram for the first two half-period Fresnel zone strips, each subdivided into smaller zones of equal phase increment. Many important applications of lasers require that the laser output be pulsed, in the sense that the laser output turns on and off in very short time periods. This decrease in lateral magnification due to the aperture position is more noticeable as the object point recedes farther from the axis, so that the image suffers from barrel distortion. 21 Plot each of the transmittance functions found in problem 20 as a function of a/w(z). Solution The visibility is given by V = 1 - t = 1 0 it where the ratio of time delay to coherence time is replaced by the corresponding ratio of path difference to coherence length. Take the speed of sound to be 340 m/s. The overall laser system, from power in (to the power supply) to power out (laser output beam), is characterized by the following component efficiencies: 80%—power supply operation 30%—arc lamps for pump light energy 70%—optical reflectors for concentrating pump light on laser rod 15%—for spectral match of pump light to Nd:YAG pump levels 50%—due to internal cavity/rod losses a. As the irradiance grows the population inversion N2 - N1 necessarily decreases since an excess of stimulated emission creates photons at the expense of the population of the upper lasing level. A typical spectral irradiance curve for a 100-W quartz-halogen filament source is given in Figure 6. a., we can write mlaa 2d at cos u1 + ... 20 (a) 2.6 A continuous He-Ne laser beam (632.8 nm) is "chopped," using a spinning aperture, into 1-ms pulses. a. minimum in reflected irradiance occurs, according to Eq. (47), when cos d = 1, or when d = 2pm and e = 2rlt cos ut = ml (50) Necessarily, this must also be the condition for a transmittance maximum. This slower saturation results because, although irradiance at a frequency equal to that of a given cavity mode interacts primarily with the group of atoms whose center frequency is at the cavitymode frequency, the irradiance also can use other groups of atoms with "nearby" center frequencies. In such case eliminate the pulse width from the plot and compare the pulse width to the range of frequencies in the superposition. 1 R2 R1 f1 f1 f2 V1 H1 n N1 H2 N2 V2 n1 f2 Figure 9 n' s Vev t These "planes" are actually slightly curved surfaces that can be considered planar in the paraxial approximation. (a) 5 = 10-7 T (b) 19.88 W/m2 3 17 R, and F. Some familiar examples of such disturbances are waves on a string, water waves, and sound waves. An axial point (shaded) from the on-axis object point 0 forms an image at and around the paraxial image point I. (b) Consider the case in which the beams are taken together. However, an excited rare-gas atom (like Ke*) has a single electron in its outer shell and so can form an ionic bond with a halogen atom (like F), which is one electron short of a filled outer shell. Quantum mechanics describes both light and matter, and, together with special relativity, predicts that the momentum, p, wavelength, l, and speed, v, for both material particles and photons are given by the same general equations: p = 2E2 - m2c4 (3c1) = h l h c = 2p 2E - m2c4 (4) v = pc2 E (5c) 5 Nature of Light In these equations, m is the rest mass and E is the total energy, the sum of the rest-mass energy mc2 and kinetic energy EK , that is, the work done to accelerate the particle from rest to its measured speed. 1 SUPERPOSITION PRINCIPLE To explain the combined effects of waves successively we first consider the simplest case of two waves with independent displacements c1 and c2 exist together? The virtual image now appears colored. Thus, the refracting power of a lens of focal length 20 cm is said to be 1 = 5 diopters. If light travels more slowly in the second medium, as assumed in Figure 6, light bends at the interface so as to take a path that favors a shorter time in the second medium, thereby minimizing the overall transit time from A to B. or more, with suitably uniform depth, shape, and spacing, has been an impressive and far-reaching technological achievement. 20 Write a computer program that incorporates Eqs. Assume that Ixx is much smaller than I. 23 The objective of a microscope has a focal length of 0.5 cm and forms the intermediate image 16 cm from its second focal point. We now apply the previous qualitative explanation somewhat quantitative. When this is the case, equal focal lengths for two wavelengths, measured as they are from their respective principal planes, do not lead to a single focal point on the axis, and longitudinal chromatic aberration remains (Figure 14a). The numerous, thin rods are multiply connected to nerve fibers, making it possible for any one of a hundred rods or so to activate a single nerve fiber. Several important cases of the combined effects of two or more harmonic waves are treated in this chapter. The average total irradiance reaching the earth's surface on a clear day is about 1000 W>m2. Thus a CCD array can be (and is) used in digital video cameras, which update the image 30 times a second. To the right of the interface, the refractive index is that of water. The wavefront from Q2 is deformed by an underwater object and interferes with the undeformed reference beam from Q1. For small magnification in M = 25 25 = = 7 13.57 In designing eyepieces, one usually seeks a large field of view and an exit pupil that is not much greater than the size of the pupil of the eye, so that incident light is not lost. Figure 5f shows the corrected vision for distant objects. A telephoto lens is a long focal-length lens, providing magnification at the expense of subject area. These variations may be described by the harmonic wavefronts B B B B B B = E0 sin kx B - Br - vt2 (28) B = B0 sin1k # Br - vt2 B (29) B B where E and B represent the electric and magnetic fields, respectively, and E0 and B0 are their amplitudes. For example, in solid-state lasers in which the active atom is doped into a transparent host, inhomogeneities in the host lead to broadening. Plot the laser output irradiance as a function of the variable reflectance R = R1 = R2 of the other two cavity mirrors. However, if one considers object points below T, the upper rays from such points, passing through the aperture, miss the lens. 5.99°, 2.16° 12. In the astronomical telescope, the exit pupil is situated just outside the eyepiece and is designed to match the size of the pupil of the eye. A) A transmission grating is expected to provide an ultimate first-order resolution of at least 1 A anywhere in the visible spectrum (400 to 700 nm). The absorption or loss coefficient a characterizes the spatial rate of change of the irradiance, that is, dI = - aI dz (20) Let us find some from the left-hand side of Eq. (20). 36 Light rays emanating from a point object on axis strike a plano-cylindrical lens with its convex surface facing the object. The geometry of this particular ray provides a means of approximately determining the virtual source separation a in terms of prism index n and angle a: a = 2ddm = 2da1n - 12 (25) Interference fringes are then described by Eq. (22), as usual. In optics, the definite integral is the integral of the time required for the transit of a light ray from starting to finishing points.1 3 PRINCIPLE OF REVERSIBILITY Refer again to the cases of reflection and refraction pictured in Figures 5 and 6. An image of the object is projected on the back wall of the box, which is lined with a piece of film. Maiman's laser used a ruby crystal as the laser amplifying medium and a two-mirror cavity as the optical resonator. The vibrational amplitudes of diffusely reflecting surfaces may be measured with high precision, and such measurements can be very useful for determining the modes of vibration of complex structures. Multilayer, thin film coatings that show little absorption in the spectral region of interest behave in a similar manner and can be used as polarization-sensitive reflectors and transmitters. When the erbium-doped fiber section is optically pumped, it serves as an amplifier for light near 1550 nm and so can be used to restore attenuated signal strength. (a) Convex lens. The accompanying increase in the magnitude of u, or of the denominator of Eq. (12), gradually decreases the amplitude of an otherwise harmonic variation. c 3i d i4 c. The cornea is roughly 12 mm in diameter and 0.6 mm thick at its center, thickening somewhat further at its edges, with a refractive index of 1.376. In step 4, one of the inverted N2 atoms, which dropped to level E1 during the stimulated emission process, now decays rapidly to the ground state E0 . The cell can be made nontransmitting by applying a 3. Accommodating Depending on the distance of the object or scene from the eye, the lens accommodates—tenses or relaxes—appropriately to "fine-focus" the image on the retina. a a0 u0 (1 ≤ cos u) 2 Illustration of the obliquity factor The effect of the obliquity factor on the secondary wavelets originating at points on the wavefront was introduced by Fresnel. (a) 100 nm, 1.22 (b) 0.084% (a) 2.81% (b) 3.17% (c) 4 26% 32.3% 2: 0.25 µm; 0.25 µm: 0.00635 (b) 15.6% (a) 227 nm and 370 nm (b) 0.25 µm (c) 11.2%, 55.1 mm, 10 mm 1:5 11 (c) 1:5 (d) 1 (a) 1.0 (b) 1.0 (c) 1 For example, from surface to substrate: MgF2 (n = 1.35), SiO (n = 1.5), ZnS (n = 2.3) (a) 81.1% (b) 98.4% (c) 99.99% 99.96% 2.24 Chapter 23 2. Recall that r1u2 is the energy per unit volume per unit frequency interval in the field. Note also that the segment of the chief ray from L2 to P', if traced backward, will appear to be coming from point N, the center of the exit pupil ExP. The gain cell has length L and is characterized by small signal gain coefficient g0 and saturation irradiance IS . Let the irradiance of such a (hypothetical) perfect image be given by I0(X, Y2 K I0(x, y2. As an example of the convolution theorem, recall the results for the Fraunhofer diffraction of a grating. Ch. 18. You will want to comment on the following considerations: Single or double refraction? ray? 191 Interference of Light 26 A fringe pattern, such as that in Figure 20, found using an interference microscope objective, is observed to have a regular spacing of 1 mm. Strong discrimination between the TE and TM modes in the incident radiation is exhibited by the curves for single-crystal gallium surfaces. twice the distance of source S above the mirror plane. A.2 4 Amnon Yariv, Optical Electronics, 3d ed. Entrance Pupil (EnP) The entrance pupil is the limiting aperture (opening) that the light rays "see," looking into the optical system from any object point. All of the stimulated emission photons have the same frequency and the same direction as the incident electromagnetic wave, whereas the spontaneous photons are emitted in—more or less—any direction with a range of frequencies described by the lineshape function. Field components and phase-locked to form constructive interference, at the position of the gate when the gate is opened, are blocked by the closed gate. The adjustable hole or opening in the iris through which the light passes is called the pupil. Plane mirrors may substitute for the reflecting prisms, but the prism's reflecting faces are easier to keep free of contamination, and the process of total internal reflection is capable of higher reflectivity. "Ruling Engines." Scientific American, June 1952: 45. Lasers with lower heat losses can sometimes be sufficiently cooled by forced air. Assume a fused silica core index of 1.446. Equation (11) also indicates that there is a frequency-dependent phase shift between the applied field and the polarization. 376 Chapter 16 Holography M2 M1 ER Subject ER y a Laser a BS Film al m Mo N2 O ES s Film (a) (b) Figure 1 (a) Off-axis holographic system. In this mode of operation, the frequencies associated with the transmittance peaks could be used to monitor and calibrate the changing frequency of the input laser field. Equation (22) can be used to obtain spot sizes at various transverse planes: w1z = 02 = W0 Spot size at the beam waist w1z = z02 = 22w0 Spot size at z = z0 w1z W z02 = Spot size in the far field (that is, for z W z0) spot size. 364 Chapter 15 Production of Polarized Light y x Unpolarized light TA Polarizer TA b Active cell Bright Image 0 Figure 18 Twisted nematic liquid crystal cell. It is transparent to the radiation emitted by the laser. The contrast of the image pattern is then I = - =(x, y) * = 0. w = 1 ay, m = n s aj = 1102102 = 4 cm 20 cm - 10 20 = - 1 20 cm 31 Geometrical Optics The image is real (because sj is positive), 20 cm to the left of the mirror vertex, and is inverted (because m is negative) and the same size as the object, or 1 cm high. To move the near point from 150 cm for the unaided eye to 40 cm for the eye/corrective lens system, the corrective lens must form a virtual image of an object placed at 40 cm from the eye at a location 150 cm from the eye. Sinusoidal waves of wavelength in-time shifted a beginning of an end axis. In this way, the laser pulse characterized at a given point of such is recorded, with corresponding decrease in spot size of the scene. PPB PPR Red Blue fB fR fR fB fR (b) Figure 14 Doublet with second principal planes separated for red and blue light. In particular, the expected at 513 nm shows up at 525 nm. To see why, we consider the simpler case of a symmetric planar or slab waveguide, shown in Figure 4. Polarized Light. A plot of reflectance versus the optical path difference c 1 = n1t associated with one traversal of the film is shown in Figure 2, where the abscissa is calibrated in ratios of n 1>l, with l = l0>n1 being the wavelength in the film. The group velocity of the signal is the velocity at which the positions of maximal constructive interference propagate. The magnitude of the film index n1 evidently determines whether the reflectance is enhanced (for n1 7 ns) or reduced (for n1 6 ns) from that for uncoated glass. Each length has a 5-db loss and each splice contributes a 1-db loss. Physical Optics Notebook: Tutorials in Fourier Optics. These Aberration Theory questions also depend on the object distance. Notice the large changes in the composite phasor A s, for small n, as the contribution from each new Fresnel zone is added. The small-signal absorption coefficient is a0 = sNT = 13 * 10-20211.0022 cm-1 = 3 cm-1 4 Modeling absorption in the the Nd:YAG crystal by a two-level system with no degeneracies is a rather drastic oversimplification of the real situation. Ring Laser We choose to illustrate the development of an expression for the steady-state irradiance output from a laser cavity by considering a ring laser consisting of three mirrors as shown in Figure 8. The result is the Wien displacement law, given by lmaxT = hc = 2.898 * 103 Imm K K2 5kB (6) and is indicated in Figure 3 by the dashed curve. (b) Linearly polarized electric field vectors whose x- and y-components are p out of phase lie in the second and fourth quadrants. Suppose this were not the case, and minimum deviation occurred for a nonsymmetrical case, as in Figure 9. The output of a stereo system is more faithful to the original signal than is the output of a telephone receiver because a greater frequency range is devoted to the process of reproduction. At any specified time and place, E = (E (30) E E0 B E0 B E0 R V n B E I Eo R E F D c1 (b) Figure 10 Plane electromagnetic wave described by Eqs. These aberrations are multimode fibers. g0 1/cm 85 20 W/cm2 10 0 g0 1cm IS 10 W/cm2 0 0 1 2 Gain length L cm) 3 561 Laser Operation but different saturation irradiances. Fringes, often called Fizeau fringes, are localized at the film, from which the interfering rays diverge. Figures 7 to 9 illustrate three such examples. Find the matrix for the simple "system" of a thin lens of focal length 10 cm, with input plane at 30 cm in front of the lens and output plane at 15 cm beyond the lens. 513 Nonlinear Optics and the Modulation of Light Nonlinear Optics and the Modulation of Light. For example, from a pulsed laser field of power 100 MW focused to a spot of radius about 5 mm. This alternative point of view emphasizes the degree of 0.2 m wave curvature or ray convergence rather than object and image distances. For each value of m, monochromatic radiation of wavelength l is enhanced by the diffractive properties of the grating. Referring to Figure 2, the angle a between actual and ideal rays from a point P of the wavefront, at elevation y, is the same angle between wavefront EgE. It emission shrinkage is 15% during processing, what wavelength is reinforced by the blue-light fringes on reconstruction? Take n = 1.50 for the glass. Silver films are most useful in the visible region of the spectrum, but their reflectivity drops off sharply around 400 nm, so that for applications below 400 nm, aluminum is usually used. All these types are discussed in the sections that follow. It follows that the retardation is very nearly inversely proportional to the wavelength. In such a case, the electric fields are said to be mutually coherent and the irradiance of the combined fields will have the form 10 = I = I1 + I2 = 2II2 cos d Mutually coherent beams (14) where d is the total phase difference at the point of recombination of the beam. 3 25 Fresnel Diffraction Strip Illustrating Figure 25 that the irradiance ... Figure 8b shows that each zone produces a different magnification, so that due to the central ray is not equal to the central ray. In this arrangement is shown in Figure 6. The apparent... Eq. (32) [illegible] The Stark transition ... If the lens has a physical system ... This is an object, a specific type of coherent light ... The "Nature of Light: What is a Photon?" OPN Trends, Vol 3., No. 1, October 2003. Let us assume that only such an excited state 2 accumulates a significant population density as a result of the interaction with the electromagnetic field. Assume that the operating temperature is 400 K and recall that neon is the lasing species. (c) Empty optical cavity, or resonator, bounded by two mirrors. (a) R = 4r2 sin2 f2 2 + a2r2 sin2 f2 (1 - r2) 16. Thus, the focusing properties of spherical lenses are invariant to rotation about their central (optical) axis. Looking again at Figure 31, imagine a screen placed on the exit side of the lens so as to capture the light from the lens. Thus, R1z2 = a ... Fundamentals of Photonics. 9 The Lick Observatory has one of the largest refracting telescopes, with an aperture diameter of 36 in. The pulse repetition time (time between pulses) can be no less than the time needed for an inverse to build, which is governed by the lifetime t2 of the upper lasing level. 14 A laser emits a monochromatic beam of wavelength l, which is reflected normally from a plane mirror, receding at a speed v. Equation (49) gives lT = li , as expected. The difference in path lengths can be controlled by a delay line (or a variety of phase shift mechanisms) in one of the "arms" of the fiber interferometer. The distances from slit to prism and from prism to eye are in the ratio of 1:4. If one mirror translates at a speed of 5 mm/s, what is the frequency of modulation of the photocurrent? 4 OPTICS OF PROPAGATION We consider now the manner in which light propagates through an optical fiber. How is the visibility modified if the path difference is doubled? A pinhole in aluminum foil, supported by a larger aperture, works well. The real refractive index experiences a sharp rise and then a fall as v increases toward and then passes through resonance, after which it increases again, approaching the value n0R = 1 at high frequencies. 5 Suppose a hologram is to be made of a moving object using a 1-ns laser pulse at a wavelength of 633 nm. Equivalently, this means that as d is varied, fringes of the pattern appear to move inward toward the center, where they disappear, or else move outward from the center, where they seem to originate, depending on whether the optical path difference is decreasing or increasing. Suppose a phase radiator or reflector is perfectly diffuse, for which we mean that it radiates uniformly in all directions. More often, the sharpness of optical images is more seriously degraded by optical aberrations due to the imaging components themselves. When the test pattern g matches the desired pattern f, the correlation image appears with a bright, central spot, and pattern recognition is achieved. If a linear polarizer with TA along the x-direction intercepts the emergent light, as in Figure 4, the transmittance of the system is zero when V = VHW . 11 Nonlinear Optics and the Modulation of Light 525 TABLE 4 VERDET CONSTANT FOR SELECTED MATERIALS V (min/G-cm) l = 589 nm Material FKD Crown glass Flint glass CS2 CCl4 NaCl KCl Quartz ZnS 0.0131 0.0161 0.0317 0.023 0.0360 0.0359 0.02838 0.0166 0.225 When the constants are evaluated and V is expressed in the standard units of min/G-cm, Eq. (15) becomes V = 1.0083l dn dl We note that the Verdet constant is proportional to both the wavelength of the light and the induced rotary dispersion in the medium. 86 Chapter 3 Optical Instrumentation Figure 33 Cutaway view of binoculars revealing composite objective and ocular lenses and image-inverting prism. Obtain a second expression for ı21/2 by using Eq. (17), 1 il 1 + = , with R21/2 , g. The Schmidt Telescope Perhaps the most celebrated catadioptric telescope is due to a design of Bernhardt Schmidt. As the grating is rotated, the dispersed spectrum moves across the slit. If the refractive index of the prism is 1.50, determine the prism angle. Thus, using a grating with fewer grooves and a larger grating constant requires that we work at a higher order m, where there is increased complication due to overlapping orders. For example, the freezing temperature of water is T = 0°C = 273 K. Also using the relation between irradiance and electric field amplitude, I = e by E E0 2 and the facts that ... Show that, subject to the approximations used in arriving at the equation E20 = E20r + a yhet cos ut 2 ba b201 yiei cos u (4) 503 Fresnel Equations Az u ur u At ut Figure 9 Comparison of cross sections of incident, reflected, and transmitted beams. Water, or a cooling oil, flows through the jacket, removing heat from the laser system. Using the expression for the fitness, F = 2eu1 I = 2eu1 2 = ... (19) Thus a 1/10-wave mirror has a figured polishing along one of the symmetric axes of such a fiber can maintain its state of linear polarization over long distances. Take the phase index to be n = 5 * 1014 Hz. a. Thus coma is absent when, for all values of u, sin u = constant sin uj The bending of a lens, found useful in reducing spherical aberration, is also useful in reducing coma. Determine the maximum width of the primary in a single slit. During the progress of ray CF from F to I in time t, however, the ray AD has entered the lower medium, where its speed is, let us say, slower. In general, all one can say, is that for constructive interference the two amplitudes add (being of same phase). In common parlance, the phase is incoherent. Just in the stationary, it is a the case we have defined. The visual range can be observed clearly, without confusion from the other beams. For the case shown, the amplitudes of E1 and E2 are equal, so, at the point of interference, the resultant disturbance is zero. Thus the condition for bright and dark fringes, Eqs. In this case, Eq. (26) can be solved in steady state to give N3 L 1 tgnB N3 L tspP T (31) It is important to note that, in the underpumped operation approximation, N3 is approximately constant and although N3 V N0, the rate k3N3 is not negligible. Optical Detectors and Displays Heated cathode Deflecting coil Vacuum tube Electron beam Anodes Screen The quasi-Fourier-transform of a image in a television the electron beam is scanned in a fixed raster pattern. 6 (17) where A, B, C, A are constants. Find optical constants to be fitted to the dispersion data of a particular material. In a good, practical dichroic absorber, is a relatively independent of wavelength; that is, the material appears transparent and yet behaves as a linear polarizer for all optical wavelengths. Label points on the x-axis with corresponding values of a and b. (a) +4 D (b) +17.5 cm; r2 = -105 cm (c) +0.714, reverse the lens 16. The small-signal gain coefficient might be approximated as g = sNj s2 ... 45 8 Is circular or elliptical polarization-oriented symmetrically about the x,y-axes). Find the phase velocity. In this glass, for a pulse with frequency components centered around 500 nm. In the latter case, suppose that 8 bits (on or off pulses) are required to represent the amplitude of an analog signal. (6)–(9). 20. Most of the common descriptions of the various frequency ranges are given in Figure 1, in which the electromagnetic spectrum is (m) (Hz) 10 6 3 1024 GAMMA RAYS 1014 1012 1A 1010 3 1022 3 1020 X-RAYS 3 1018 1 nm 108 V (Vacuum) 3 1016 UV (Near) 1 mm 106 (Near) OPTICAL 104 IR 102 1m 1 m-WAVES (radar) (UHF-TV) (VHF-TV) Visible spectrum 0 3 1012 (Far) 1 cm B G 3 1014 380 nm R 770 nm 3 1010 3 108 (FM-radio) 102 3 106 (AM-radio) 1 km RADIO WAVES 104 1000 km 106 108 (AC power) 1 104 3 102 3 Figure 1 Electromagnetic spectrum, arranged by wavelength in meters and frequency in hertz. 6 ATTENUATION The irradiance of light propagating through a fiber invariably attenuates due to a variety of loss mechanisms that can be classified as extrinsic and intrinsic. Introduction to Lasers and Their Applications. If light of wavelength 630 nm is used, compute, using the Cornu spiral, the irradiance of the diffraction pattern on the axis at the screen. A third ray serves as a convenient check on the accuracy of the first two chosen rays. When the instrument is used spectrally to select individual frequencies in a discrete spectral source or to allow a narrow wavelength range of spectrum through the exit slit, it is called a monochromator. (a) r11 = -3.5435 cm, r22 = 12.6576 cm (b) f2 = 3.0000 cm, f2 = 5.0026 cm, f' = 5.0026 cm f2 = 0 PUP = -0.3695 cm - 1, P2P = -0.1695 cm - 1, a10 = 0.01802, a20 = 0.00928 (d) yes 23. A brief discussion of interference gratings and several conventional types of grating spectrographs ends the chapter. -2.5 ft, -180 + 3. The law also requires that ray 3, incident normal to the surface 1u2 = 0, be transmitted without change of direction 1u2 = 02, regardless of the ratio of refractive indices. For the example used previously, where n1 = 1.46 and n2 = 1.45, we have c>2 = 1>292. (26) though (29) must sum to zero. If the retardation plate introduces phase differences other than p, the light is rendered elliptically polarized, and some portion of the light will still be transmitted by the analyzer. The source has a spectral distribution close to that of a graybody at 6000 K. Therefore, the propagation constant k is the spatial frequency of the wave. Observation plane 589.3 nm a 1 mm S Double slit 0.04 mm 15 cm 30 cm Problem 18 Straight edge 60 cm a 2 mm 120 cm Figure 23 Problem 15. For a TV station using a 300-MHz carrier, this ratio is 300 MHz/6 MHz, or 50; for an optical fiber using a carrier of 1-mm wavelength 13 * 108 MHz2 to carry the same TV signals, the ratio is 13 * 108 MHz2>6 MHz, or 50,000,000! Currently, optical fibers carry such a bandwidth theoretically available to optical systems means that the advantage of the bandwidth of individual wavelength is a considerably matched to the multiplexed one. The fitness of the system of M1 to be made perpendicular to that of M2. In general, the averaging time of physical detectors greatly exceeds an optical period 110-14 - 10-15 s2. Clark Jones.1 First we develop two-element column matrices or vectors to represent light in various modes of polarization. (c) Tungsten lamp with pinhole and filter: Stars are so distant that imaging techniques are unable to resolve their diameters. 13 Two headlights on an automobile are 45 in. Note that the rate coefficients for stimulated emission and stimulated absorption are equal. Combination of the two thus shifts the wavelength of zero net dispersion toward a longer wavelength of about 1.31 mm in a typical fiber. If the system is to be Q-switched with a pulse repetition rate of 1 kHz and a pulse width of 60 ps. (c) estimate the peak power in a Q-switched pulse and (d) estimate the energy in each pulse. Diffraction Grating The angular positions u of the grating order m are found from the grating equation. If the amplitude r = r1x, y2 of the reference beam can be regarded as constant over the essentially plane wavefront. The first term, EH1 = E12 + E22B = E12 + E22 + E12 + E22 + 2E1 = E2 (10) represents a reference beam modulated in amplitude but not in phase. In the former case, all rays of a parallel beam incident on the surface obey the law of reflection from a plane surface and therefore reflect as a parallel beam; in the latter case, though the law of reflection is obeyed locally for each ray, the microscopically granular surface results in I t is of interest to note here that a similar principle, called Hamilton's principle of least action in mechanics, that calls for a minimum of the definite integral of the Lagrangian function (the kinetic energy minus the potential energy), represents an alternative formulation of the laws of mechanics and indeed implies Newton's laws of mechanics themselves. Reflection coefficient (Total) between a series of maxima and minima. When d = ml, an interference principal maximum occurs. Figure 3 Neighboring reflection grating grooves illuminated by light incident at angle ui with the grating normal. Since the total exposure 10 m2 of the film depends on the product of irradiance and d, a desirable total exposure may be met in a variety of ways. When the wavelength and the object distance (1 and d) are fixed, the length of the resonator is changed so that the resonance conditions 1 and 2 can be met, so that f (within 2 percent) 2ri so can a microscope. The minimum is in the medium. (7) to (9) can be generalized further to yield any initial displacement, therefore, by the addition of an initial phase angle w0 to the phase. Even so-called monochromatic light, unless it has infinite spatial extent and has been in existence for all time, possesses a spread of wavelengths, however narrow, about its wave mid-wavelength. Calculate its focal length and refracting power as a thin lens in air. Thus, in 1 m of fiber, there are approximately 1.0/ut = 1 or 6500 reflections! Table 1 lists various core and cladding possibilities. Let us write the equations for stimulated emission, the population inversion, and so the gain coefficient, in atoms within, roughly, one homogeneous gain bandwidth of the corresponding cavity-mode frequency. Further, for Eqs. Minimizing dt for all modes requires a value of np = 2. Xmin = 1 The resolution of a microscope is roughly equal to the wavelength of light used, a fact that explains the advantage of ultraviolet, X-ray, and electron microscopes in high-resolution applications. The annual average of total irradiance just outside the earth's atmosphere is the solar constant, 1350 W>m2. Solution As given, s = 25 cm, R = 10 cm, n1lens2 = 1.50 and CL = 5 cm. and a focal length of 56 ft. As shown, the aperture stop (AS) in front of the lens determines the extreme (or marginal) rays that can be accepted by the lens. This is because photon absorption and stimulated emission processes affect the population densities N1 and N2 in such a way as to drive the system toward a 29 Suppose the average power consumed to operate the TE would be as Pump = Ptot 57 W w = 1900 W efficiency 0.03 Two-Mirror Linear Cavity The analysis leading to the output irradiance for the more common two-mirror linear laser is somewhat more complicated than that given for the ring laser, but nevertheless can be carried out in a similar fashion.6 The result for a two-mirror cavity like the one shown in Figure 9 (see problem 19) is Iout g0122 - ln A R1R2 B 12R1 + R1 A 1 + 2R2>R1 B e 1 - 2R2>R1 = ... for example, Joseph T. What is the maximum depth of hologram fringes so that the appropriate signal is... If the pulse tuned to is limited in the direction um , the net path difference from the two slits is 1 + 2 . As loss is increased, the fringes disappear when equality in Eq. (38) is satisfied. The eyeglass prescription is: R: -2:00 -1.00 * 180. 3 A conventional 1-mm-thick compact disc (CD) can store 1 Gb of information in the form of pits, all of the data stored in the top 1-mm-thick layer of the CD. In problem 3 you will be asked to show that a significant number of hydrogen molecules will be in the first excited rotational energy state at room temperature. If myopic astigmatism is present, for example, vision is faulty on two counts: Liquid-Crystal Displays (LCDs) The atoms or molecules in a liquid are arranged in a completely disordered fashion, whereas those in a (solid) crystal are regularly arranged in a periodic fashion. How do they arise and where do they appear? Regarding this result as describing instead the maximum slit separation d, given a source dimension s, we have for the spatial coherence width ls = ls 6 l1 s (37) As is restricted to smaller fractions of this value, the fringe contrast is correspondingly improved. (b) For the second ... t 2 Laser Operation ... Figure 29 Focusing Questions: refers to a lens surface that is both concave and convex. Fundamentals of Photonics. If the magnification of the system is 15x, what is the optical tube length? The distance between the two "source" is measured. Measurements of the distance between the two "key ray of reflection" of light among the ... a grating is needed that is able, working in first order, to resolve the red doublet produced by an electrical discharge in a mixture of hydrogen and deuterium: 1.8 A at 6563 Å. E3 k32 E2 gsl̅p k31 hsp st k30 k21 E1 k30 E0 k10 E0 Laser Operation INTRODUCTION In this chapter we give a quantitative treatment of laser operation. Since N2 is greater than N1 , however, and B21 = B12 , the rate for stimulated emission, B21g1n2r1n2N2, is greater than the rate for stimulated absorption, B12g1n2r1n2N1 . The discreteness of the energy of light quanta would be very evident in this case. Thus, if a volume hologram is illuminated at a given angle ui, only the single wavelength that satisfies the Bragg equation locally, where planar spacing is d, is reinforced and appears as a brightly reflected beam. In this idealized case we have a perfectly monochromatic beam, an unrealized concept. Optical fibers have found a variety of uses. The contrast... (5) and (6). Its radius... Fourier Series Examples ... Normalized principal planes and nodal points are constructed for an arbitrary real object. Simplifying, we find IP = E1b sin b rb2 cos u2 (b) Thus, the amplitude of the resultant field at P, given by Eq. (9), includes the sinc function sin b2> b, where b varies with u and thus with the observation point P on the screen. Another remedy for spherical aberration is achieved by combining positive and negative lenses in an arrangement such that the spherical aberration from one tends to cancel that from the other. One such instrument is described later in this chapter. In the observational arrangement shown in Figure 14, the reflector... aperture, as indicated in Figure 4. The deviation from the law to the nearest lines, no point of the ... The thin lens relation . . . plane with the focused ... ft STOKES RELATIONS In order to account for the multiple internal reflections in a thin film, we must develop some relations for the reflection and transmission coefficients for electric fields incident on an interface between two different media. Recall that the diffraction envelope maximum occurs when b = 0. Show that, as shown, where is the far-field path difference for light rays from the m ... (d) Pupil ... Interference of Light... The Michelson interferometer... Consider the field diffracted... 1 E0 a m1 NT (2) Fig... with a 0.65 mm, has a beam ... The diffraction region is illustrated in Figure 14. (a) Calculate the time-averaged and maximum radiation pressure... Consider the radiation ... The magnetic fields ... The Tully wavefront ... The object ... light ... 1-2 Figure 5 (a) Polarization ... is shown ... Figure 20 ... Consider a symmetrical ... lenses ... The optical... One ... Figure 26 The resolution ... A radiation ... Optical Lenses ... Dispersive ... The laser ... The interference ... In general ... Figure 14 Thin lens ... Light with ... Polarized ... For ... The Fresnel ... Nonlinear ... Chapter 9 Coherence Figure 21 ... The cavity ... (a) ... (b) ... Example ... Figure 1 ... Fraunhofer Diffraction ... Figure 6 ... It is ... The ... Find ... Hence ... Calculate ... Thus ... Show that the ... Determine ... The optical ... 28 A thin ... Since ... In ... For ... When ... A ... The phasor ... The transfer ... An ... Notice ... Compare ... 8 ... (c) ... Thus, in ... Let ... Assume ... where ... which ... The ... 10 ... Hence, the transform pair takes the form +q 1 g1kx , ky2e-i1xkx + yky2 dkx dky f1x, y2 = 12p22 -q (6) +q g1kx , ky2 = O f1x , y2 ei1xkx + yky2 dx dy (7) -q Any nonperiodic function of two variables f(x, y) can thus be synthesized from a distribution of plane waves, each with amplitude g1kx , ky2 and constant phase, such that xkx + yky = constant (8) The quantities kx and ky are the spatial frequency components needed in the expansion to represent the desired function f(x, y). We now show that Eq. (17) is equivalent to the Bragg diffraction condition. By far the largest amount of light energy is diffracted into the central maximum. The total energy density is the sum u = uE + uB = 2uE = 2uB or u = e0E2 = a (35) Consider next the rate at which energy is transported by the electromagnetic wave, or its power. (Courtesy Carl Zeiss, Inc., Thornwood, N.Y.) angles a¿>a, as shown. We may argue rather neatly that when minimum deviation occurs, the ray of light passes symmetrically through the prism, making it unnecessary to subscript angles, as shown in Figure 11.

rapid decrease in the subzone phasor magnitudes 1b1 , Á 2 the phase angle of A 1 relative to the reference direction is less than p>2. Thus a reduction in the population density of state 2 must be accompanied by an increase in the population density of state 1. If the roles of points A and B are interchanged, so that B is the source of light rays, Fermat's principle of least time must predict the same path as determined for the original direction of light propagation. Determine the luminance of the sun. Let light from this source be incident on a scanning Fabry-Perot interferometer of nominal length d = 5 cm. The transmission function of a given object in the aperture plane can be simultaneously correlated with many different reference functions by separating the reference functions as horizontal strips, or channels, on the mask. To assist in the calculation, point G is shown midway between A and C at the foot of the altitude BG in the isosceles triangle ABC. Although such scattering is much less effective, per oscillator, than Rayleigh scattering, the density of oscillators in this case leads to considerable scattering. Also, the distances r and r¿ are no longer so much greater than the size of the aperture that Fraunhofer diffraction applies. Using nf = 1 for air, the condition for brightness is 2d cos ut = ml (15) Other beams from different points of the source but in the same plane and making the same angle ut with the axis satisfy the same path difference and also arrive at P. For example, if the aperture diameter 4.5w = 1 cm, the collimated beam length 2z0 is equal to 24.5 m for He-Ne light at l = 632.8 nm and 1.46 m for CO2 light at 10.6 mm. Let us now examine these figures in turn. 2 a. Such a review naturally begins with a discussion of the interaction of light and matter in thermal equilibrium. Reading, MA: Addison-Wesley Publishing Company, 1963. Thus, for the single slit ¢z = w, and by S(y) 1.5 2.5 E 0.5 1.0 2.0 P⬘ O⬘ S y O w ⱖ0.5 P ⱖ0.5 ⵯy F ⵯy 0 G 0.5 ⱖ2.0 p q (a) ⱖ1.0 E⬘ ⱖ0.5 ⱖ2.5 ⱖ1.5 (b) Figure 15 Fresnel diffraction from a single slit (a) and its amplitude representation on the Cornu spiral (b). And today, some 60 years later, the puzzle of tweedledum and tweedledee lingers. The radiant power density, or irradiance, Ee 1W>m22, measures the time average of the square of the wave amplitude. Two other closely related applications of the Pockels cell are illustrated in Figures 6 and 7. (b) 241 Coherence Example 3 When Michelson used this technique on the star Betelgeuse in the constellation Orion, he found a first minimum in the fringes at ls = 308 cm. Each procedure modifies the top layer of the 530-mm-thick cornea, while preserving the structural integrity of the layers underneath. (1)–(3) can be written as B E0 = EyN B E0r = EryN B E0t = EtyN (11) Here, E, Er and Et are the complex field amplitudes associated, respectively, with the incident, reflected, and transmitted waves. Express the answer as some number times the unobstructed irradiance there. For normally incident light, however, the grating equation limits the maximum wavelength (at u = 90°!) under these conditions to 200 nm. Also, since ' E0 = x RCP Notice that one of the elements in the Jones vector for circularly polarized light is now purely imaginary, and the magnitudes of the elements are the same. However, this large photon number density initiates sufficient stimulated emission events Laser Operation 571 2.5 1016 Number density (cmⱖ3) 2.0 1016 1.5 1016 Ninv 1.0 1016 20Np 0.5 1016 0 0 0.2 0.4 0.6 0.8 1 1.2 1.4 Time (ms) to drive the population inversion below its threshold value, at which time cavity loss exceeds gain and the photon number density begins to decrease. Electromagnetic (EM) waves are produced by 7 Nature of Light accelerating charge distributions, carry energy, and exert forces on charged particles upon which they impinge. Iodine reacts with the deposited tungsten to form the gas tungsten iodide, which then dissociates at the hot filament to redeposit the tungsten and free the iodine for repeated operation. Notice that the off-axis system illustrated in Figure 2a produces a hologram in which the two first-order beams are separate in direction from each other and the zeroth-order beam. Between positions of common phase, since the fields have different frequencies, the fields tend to destructively interfere. The amount and location of pigment in the iris determine whether the eye looks blue, green, gray, or brown. Thus, f = - R 7 0, e 2 6 0, concave mirror convex mirror (13) s f (b) ho a ui hi ur and the mirror equation can be written, more compactly, as 1 1 1 = + s s¿ f F C a (14) s s (c) 5 Although this set of sign conventions is widely used, the student is cautioned that other schemes exist. Goodman, Joseph W. Absorption and emission of electromagnetic waves is therefore an important mode of energy exchange between systems. A critical angle of incidence uc is reached when the angle of refraction reaches 90°. Example 1 A traveling wave in a string has a displacement from equilibrium given as a function of distance along the string x and time t as y(x, t) = (0.35 m) sin[(3p/m) * - (10p/s)t + p/4)] Determine the wavelength, frequency, velocity, and initial phase angle. This source is a cylindrical tube or rod of refractory material (zirconia, yttria, thoria) heated by an electric current and useful from the visible to around 30 mm. Of course, the Jones calculus can handle a case where polarized light is transmitted by a series of polarizing elements, since the product of element matrices can represent an overall system matrix. (b) Refraction by a thick lens. (c) 0 (d) 1100 W/m2 (e) 1.11 × 105 W/m2 (f) For = 1/cm: N0 /NT = 0.993; for = 0.01/cm: N0 /NT = 0.99993 reasonable for both (g) 1100 W/m2; 1.10 × 105 W/m2 7. 0 ⱖ25 ⱖ50 0.7 0.8 0.9 1 1.1 1.2 1.3 Wavelength (m) 1.4 1.5 1.6 1.7 Example 3 Using Figure 13, calculate the pulse spread due to material dispersion in pure silica for both a LED and a LD light source. Even when the signal is zero, the reference beam is of sufficient strength to stimulate the emulsion within its region of linear response to radiant energy. Thrierr, Atlas of Optical Phenomenon, Plate 16, Berlin: Springer-Verlag, 1962.) Example 3 Find the diameter of the Airy disc at the center of the diffraction pattern formed on a wall at a distance L = 10 m from a uniformly illuminated circular aperture of diameter D = 0.5 mm. the train of reflections. We wish to find next the partial differential equation that is satisfied by all such waves, regardless of the particular function f. Note that the beam spreads while maintaining nearly spherical wavefronts that change radius of curvature as the beam propagates. Take the electric fields of the individual beams to be E1 = 2 cos1ks1 - vt2 E2 = 5 cos1ks2 - vt2 1kV>m2 1kV>m2 Interference of Light Let us determine the irradiance contributed by each beam acting alone and that due to their mutual interference at a point where their path difference is such that k1s2 - s12 = p>12. (See Figure 9.) 16 Evaluate modal distortion in a fiber by calculating the difference in transit time through a 1-km fiber required by an axial ray and a ray entering at the maximum entrance angle of 35°. Many of the quantum detectors discussed in the next section are better suited to high-frequency operation. To produce a 1 + 2 magnification in the construction of Figure 16c, where s¿ must itself be negative, we modify Eq. (15) to give the general form m = - The following example illustrates the correct use of the sign convention. How long is the image of the meter stick? So as ¢ varies by one wavelength, the phase k¢ varies over an entire cycle of range 2p. Thus, as atoms funnel rapidly from pump levels E3 to E2 , they begin to pile up at the metastable level, which functions as a bottleneck. For real mirrors with absorption losses, the maximum transmittance is somewhat less than unity. , when a monochromatic field of frequency n¿ and irradiance I is incident on an assembly of atoms like the one depicted in Figure 11a is RSt. Abs. For this ray the deviation angle dm is given by dm = a1n - 12. The unpolarized light is represented by two perpendicular (x and y) vibrations, since any direction of vibration present can be resolved into components along these directions. The image is turned inside out. Objective lens Star light 12 Assume that a 2-mm-diameter laser beam (632.8 nm) is diffraction limited and has a constant irradiance over its cross section. If there were several nearby point sources emitting light of the same frequency but with random relative phases, the spatial coherence of the resulting wavefield would be reduced. Assume the crown glass lens to be equiconvex. In symbolic form, we have, from Eq. (13), c yf A d = c C af B y0 dc d D a0 (21) which is equivalent to the algebraic relations yf = Ay0 + Ba0 af = Cy0 + Da0 (22) 1. To do so, we should first relate the round-trip phase shift d to the frequency of the input field n. Symbolically, g1k2 = Ḉ-5f1x26 (3) f1x2 = Ḉ-15g1k26 (4) Here Ḉ and Ḉ-1 represent, respectively, the Fourier-transform operation and its inverse. From this approach, one can reason that the diffraction pattern of the slit is symmetrical about its center and that the irradiance, while oscillatory, is never zero. Note that the Rayleigh range z0 is also a convenient measure of the distance over which a beam spreads appreciably in the near field. A lens of focal length 60 cm is placed behind the slit. For example, 1 dm of turpentine rotates sodium light by - 37°. For propagation between two points in the same uniform medium, the path is clearly the straight line joining the two points. On the other hand, the refractive index of the ordinary ray is a constant, independent of direction. For an assembly of gain atoms each of mass M at temperature T, ¢nD = a 8kBT Mc2 1>2 ln122b (52) n0 Figure 11 shows the lineshape function g1n2 for a Doppler-broadened gain medium consisting of atoms each of which has a homogeneous linewidth ¢nH . Dye lasers emit radiation in the visible region of the spectrum, and a few different dyes are sufficient to provide coherent radiation tunable across the entire visible spectrum. 1 + s11œ = 16 gives OP imaged through L1: s1 = 18 cm, f1 = 6 cm; 18 s1œ = 9 cm right of L1 or 5 cm to the right of L2 . (46) and (47) together with Figure 14 to obtain values for w02 and z2 . 348 Chapter 14 Matrix Treatment of Polarization 5 Find the character of polarized light after passing in turn through (a) a half-wave plate with slow axis at 45°; (b) a linear polarizer with transmission axis at 45°; (c) a quarter-wave plate with slow axis horizontal. The concept is defined 232 S Path Pa th 2 1 Chapter 9 Coherence S1 P S2 Figure 8 Interference at P due to waves from S traveling different paths. To see that this is not always the case, look at Figure 1b, where the aperture stop is behind the lens (a rear stop), as in most cameras. Both its location and size (magnification) are shown. Beam-shaping optics with D Ú 4.5w transmit essentially 100% of the beam power without superimposing additional diffraction effects on the beam. Cambridge: Harvard University Press, 1962. Broader regions of low reflectance result for l>4 – l>4 coatings when the substrate index is larger than that of the adjacent film layer, that is, ns 7 n2 . The labor involved in the design of a suitable lens that meets particular specifications within acceptable limits has been reduced considerably with the help of computer programming. The directly propagated light could therefore be represented by a phasor in the vertical direction, making an angle of p>2 with a1 . Find the FWHM 2¢n1>2 of the transmittance peaks. One also inputs the desired overall focal length of the achromat. A geometrical relation exists between the radius rm of the mth-order dark fringe, the corresponding air-film thickness tm , and the radius of curvature R of the air film or the lens surface. Gas atomic lasers are typically Doppler broadened and have low efficiencies (less than 1%). Evidently, the electric field vector may reverse direction on reflection. Optical data processing represents a fruitful convergence of the fields of optics, information science, and holography. However, spherical-mirror cavities also have a more complex transmittance spectrum than do the flat-mirror cavities just considered. To extend the usefulness of the spectrograph farther into the ultraviolet, for example, prisms made from quartz 1SiO22 and fluorite 1CaF22 have been used. (Courtesy Corning Glass Works.) (b) Spectral attenuation for all-plastic fiber cable. By such optical means, two-dimensional pictures or text are processed at once, without the necessity of sequential scanning of the object. Light, Vol. An unpolarized beam is B conveniently represented by two perpendicular E-vibrations. The convolution theorem (see problems) states that the Fourier transform of the convolution of two functions is equal to the product of their individual transforms. The shortest distance L from A to B is taken by the axial ray; the longest distance L¿ from A to B is taken by the steepest propagating ray that reflects repeatedly at the critical angle wc . The chapter next treats standing waves that result from the superposition of a harmonic wave with its reflected counterpart. In this example we have assumed that the medium to the right of the spherical surface extends far enough so that the image is formed inside it, without further refraction. Although simple in structure, it is a high-resolution instrument that has proven to be a powerful tool in a wide variety of applications. This must be the case, since AS and EnP are, by definition, conjugate Optical Instrumentation planes: The edges of EnP are the images of the edges of AS. Figure 15a shows, in four steps, what happens to a typical atom in the laser medium during the creation of a laser photon. When AB = ml, the grating Eq. (34) follows immediately. In doing so we have implicitly assumed that the irradiance of the field is constant temporally and spatially. Now the quantity r2 is just the reflectance R: R = E0r 2 Pr Ir = a b = r2 Pi Ii E0i Comparing Eq. (47) with Eq. (42), it follows that the transmittance T is expressed by the relation cos ut 2 bt T = na (48) cos u 504 Chapter 23 Fresnel Equations Notice that T is not simply t2 since it must take into account a different speed and direction in a new medium. The stored charge contributed by each pixel, a measure of the local irradiance, is electronically scanned to produce an electronic record of the image. In the process, N2 grows to a large value. This procedure is outlined next and illustrated in Figures 22 and 23. In this case, af = Cy0 , independent of a0 . The carrier wave can be modulated to contain the signal information in various ways, usually by amplitude modulation (AM), frequency modulation (FM), or digital modulation. Using Eq. (52), we conclude that the exit pupil for this pair of binoculars is 5 mm, a good match for the normal pupil diameter. Boundary Conditions for TM Waves Before pursuing the significance of Eqs. The lower curves have the same small-signal gain coefficient 20 g0 2/cm IS 10 W/cm2 IL (W/cm2) 15 Figure 7 Irradiance output IL from a gain cell as a function of the length L of the gain cell. In addition, as we show later, the rate at which light energy stored in an optical cavity decreases over time due to transmission through and absorption by the cavity mirrors is directly related to the FWHM, 2¢n1>2 , of the transmittance peaks of the same cavity used as a Fabry-Perot interferometer. A variation in transmittance of the type T = T0 + Tm cos21ar22 is produced, and higher-order images are eliminated. Typically, two blackened sensitive elements are used in adjacent arms of a bridge circuit, one of which is exposed to the incident radiation. In this way, the spectral range of the incident light is limited by filtering until overlap is removed and each line can be correctly identified. How many visible 1l = 555 nm2 photons/s would correspond to a detected power of 6.63 * 10-16 J>s? The third number refers to the orientation of the cylinder axis, specifying whether the axis of the cylinder is to be vertical, horizontal, or somewhere in between. The second formulation is suggested by Figure 9. These demultiplexing relations are explored in Example 4 and problem 28. 405 406 Chapter 18 Matrix Methods in Paraxial Optics 8 SIGNIFICANCE OF SYSTEM MATRIX ELEMENTS We examine now the implications that follow when each of the matrix elements in turn is zero. The reflected light is admitted into a prism spectroscope. (a) At laser turn on, the gain coefficient has its smallsignal value and three cavity modes are above threshold, and so the irradiance grows at these frequencies. The wave vector E of the incident wave is chosen in the +y-direction, so that the wave is linearly 491 492 Chapter 23 Fresnel Equations y n2 Et Interface kt O r Br Bt ut Plane of incidence Er P ur kr n1 E u z k B x Normal Figure 1 Defining diagram for incident, reflected, and transmitted rays at an xyplane interface when the electric field is perpendicular to the plane of incidence, the TE mode. The mode-locking "gate" can be any of the devices, described earlier, that could be used as Q-switches, provided that the gate can be opened and closed over a time period shorter than a cavity round-trip time. Then P2 = 12 e0x2E 20 + 12 e0x2E 20 cos 2vt (5) Evidently, the second-order polarization P2 consists of a term of twice the frequency of the applied optical field as well as a constant or DC component that represents optical rectification. Compare with the

about, consider the formation of closely spaced interference surfaces within a thick emulsion by using coherent subject and reference beams with the largest angular separation possible, 180°, as in Figure 5. Instead of 2v1 : v3 , as in second harmonic generation, it is possible to have sum frequency generation such that v1 + v2 : v3 or difference frequency generation such that v1 - v2 : v3 . Use the expression for the focal length of a thin lens, n2 - n1 1 1 1 = a b, with careful attention to thinf n1 R1 R2 lens sign conventions to obtain the focal length of the thin-lens output element. 2 sin2 0.575x) I0 sin (1.151y) 0.438x2 y2 (b) 5.46 mm along x; 2.73 mm along y (c) 0.895 along x; 0.629 along y (d) 0.005 (a) 90° (b) 11.5° (c) 5.7° ^ = (/D)(1/ cos) (b) 4.7%, 1.8%, 0.84% for m = 1, 2, 3, respectively m = 0; 1/2 = 30° (a) 120° (b) Ip = (19)Imax (c) Ip = Imax (d) Ip = 3Iav 8. For the case plotted in Figure 14a and b, a = 6b, and the missing orders are those for which p = ; 6 , ; 12, and so on. OA OA (a) OA 6 OPTICAL ACTIVITY OA Certain materials possess a property called optical activity. 6 DIFFRACTION FROM MANY SLITS For an aperture of multiple slits (a grating), the integrals of Eq. (23), together with Figure 13, are extended by integrating over N slits. The Ramsden eyepiece of a telescope is made of two positive lenses of focal length 2 cm each and also separated by 2 cm. When halfwave voltage is applied, the polarization state of the laser radiation is rotated by 90°, so that it can be extracted with the help of the polarizing prism, as shown. At normal incidence 1u = 0°2, for both TE and TM modes, Eqs. For objectives with numerical apertures over 0.30, the cover glass has increasing influence on the image quality, since it introduces a large degree of spherical aberration when oil immersion is not involved. This yields a replica of the grooves in a metallic element, which is called a shim. The presence of the letter is indicated by the formation of a bright spot in a location that indicates the position of the letter in the text. Determine the attenuation in db/km for fibers having an overall fractional power loss of 25%, 75%, 90%, and 99%. As a result, the thickness of the lens along the axis increases 437 Optics of the Eye to 4.0 mm, and the distance from cornea to the front surface of lens is shortened to 3.2 mm. Resnick, Robert. Every delay in phase in ES now shows up as a phase advance. As we mentioned, the finesse is a useful figure of merit because it is the ratio of the separation between adjacent transmittance peaks (that is, the cavity free spectral range) to the FWHM of a transmittance peak. Digital cameras work in this fashion. Using this process, the hologram can be developed and viewed quickly and so the holocamera can be used for rapid inspection and analysis in an industrial environment. Here, we will categorize such polarizers in terms of their effects, which are basically three in number. Does the eye see an image erect relative to the object? As indicated by Eq. (2), if the light is not incident along the normal, the maximum diffractable wavelength can be increased; when ui nears 90°, it is twice as much, or 400 nm. The irradiance in each of these six modes, therefore, begins to grow. 210 Chapter 8 Optical Interferometry over the performance of comparable prism and grating instruments. The single beam produces multiple coherent beams in the interferometer, and the emerging set of parallel rays are brought together at a point P in the focal plane of the converging lens L. If the pinhole aperture is opened sufficiently to accommodate a converging lens, we have the basic elements of the ordinary camera (Figure 20). These two image detection systems are discussed below.1 Photographic Film Until the recent widespread use of digital cameras, photographic film was the most common medium used for image detection and recording. 1 1 b M1 M2 This is Abbe's method for finding the focal length of a lens. In this case, the resultant wave is in step with the individual waves being superposed. The irradiance due to the spontaneous emission is typically much less than the saturation irradiance of the gain medium. The negative sign indicates an inverted image. You will also need the definite integral +q 2 L-q 242 Chapter 9 Coherence for points, let us assume "good" spatial coherence occurs within a length that is 25% of the maximum value given by Eq. (38). Holding the pencil fixed, close one eye at a time. Three different electron beams are typically used and each beam reaches "dots" of only one of the three types of phosphors on the screen due to a grille or mask that blocks the beams from striking the wrong type of phosphor. The spot size w(z) at the beam waist 1z = 02 is defined as w0 . Since 1 eV = 1.6 * 10-19 J, we have mc2 = 5.11 * 105 eV = 0.511 MeV. (d) Use of a stop to artificially "flatten" the field of a lens. In what follows, we discuss each of these visual functions in somewhat more detail. Summarizing these results for the case of internal reflection, fTM = 0, p, u 6 upe upe 6 u 6 uc 2sin u - n b , cos u 7 uc u 6 uc fTE = c - 2 arctana 2sin u - n b , cos u 2 (38) 2 2 (39) u 7 uc Phase shifts for both TM and TE modes and for both internal and external reflection are summarized in Figure 8. Eye relief, that is, the distance from eye lens to exit pupil. Although reflection at the polarizing angle from a dielectric surface can be used to produce linearly polarized light, the method is relatively inefficient. Find the relative likelihood Pk = 1>Pk = 0 that a hydrogen molecule will be in its first excited vibrational state in thermal equilibrium at room temperature, T = 293 K. Let the irradiance of the incident light on the first polarizer be I0 . For the case described in (a), show that the location of the beam waist can be written as Z2 = c. (a) Integral laser device with output laser beam. The last equality in Eq. (31) defines the transfer matrix elements, m11 , m12 , m21 , and m22 for the case at hand. A grating may be designed to operate either as a transmission grating or a reflection grating. These are given in Figure 6, together with a mnemonic device to assist in recalling them quickly. In viewing a hologram, this wavefront is reconstructed or released, and we view what we would have seen if present at the original 372 Holography scene through the "window" defined by the hologram. Differences in frequency imply differences in wavelength and, if the medium is dispersive, differences in velocity. If the beam diameter is 1 cm, determine the number of resolvable spots. Thin Film Physics. In the second order, this figure improves to 0.0063 nm, and so on. The real image formed by the objective is observed with an eyepiece, represented in the figures as a single lens. The plate acts as a perfect window for TM polarized light. Let cn- ¢t be the incremental rate of change of the number n of photons (traveling in the + z-direction) through a small volume ¢V of cross-sectional area ¢A and length ¢z due to interaction with a gain medium. How many independent telephone channels can the system accommodate? Microscopy Another useful application of holography is in microscopy. 454 Chapter 20 Aberration Theory The variation of n with l in the neighborhood of lY may be approximated using the red and blue Fraunhofer wavelengths, lC = 656.3 nm and lF = 486.1 nm, respectively: nF - nC 0n 0l lF - lC (40) The dispersion constant for the glasses may be introduced by expressing the terms of Eq. (39) as K1 n1F - n1C n1D - 1 P1D 0n1D = K1 a ba b = 0l lF - lC n1D - 1 1lF - lC2V1 (41) K2 n2F - n2C n2D - 1 P2D 0n2D ba = K2 a b = 0l lF - lC n2D - 1 1lF - lC2V2 (42) where we have used Eqs. (a) 10, 5, −2.5 diopters; 12.5 diopters (b) 8.33 m−1 , 4.17 m−1; 24 cm 30. Any three of the four-level rate equations, together with Eq. (30), can be solved simultaneously to give the steady-state population densities of the four levels and so to find the steady-state population inversion Ninv = N2 - N1 . The rods are located more densely toward the periphery of the retina. 10 A film of magnesium fluoride is deposited onto a glass substrate with optical thickness equal to one-fourth the wavelength of the light to be reflected from it. Figure 16b shows the same process for an incident spherical wave. 517 518 Chapter 24 Nonlinear Optics and the Modulation of Light of symmetry, many tensor components may vanish or become equal to others, reducing the total number of independent elements7 required to represent a particular crystalline material. When the aperture stop is placed at the position of the lens, such distortion does not occur. Light entering from the left encounters six spherical surfaces whose radii of curvature are, in turn, r1 to r6 . Diode lasers do have several unfavorable characteristics. For a wavelength around 500 nm, determine its mode number, its finesse, its minimum resolvable wavelength interval, and its resolving power. Fewer zones make a contribution from the upper half of the wavefront relative to P¿ than they do relative to P. This system provides an experimental means of comparing, or correlating, the light pattern in the image of the object in the aperture plane and the pattern contained on the mask. For higher magnifications, objective lenses with focal lengths in the range of 4 to 16 mm incorporate some fluorite elements, which together with the glass elements provide better correction over the visual spectrum. The vision in the woman's left eye is corrected with a contact lens of power -7 diopters, and the vision in this woman's right eye is corrected with a contact lens of power -5 diopters. Since the two beams travel different paths from point A onward, a relative phase difference develops that can produce constructive or destructive interference at P. We choose the forms of the fields shown in the preceding equations in order to lead to a standard expression for the irradiance at point P in terms of the coherence properties of the source field. The first-order 1m = 12 spots above and below the central spot represent the fundamental frequency nY1 = 1>d. In the figure, the process is assumed to be 100% efficient. A motion picture depiction of the sound wave of Figure 5 would show the wavefronts moving in the positive x-direction at the wave speed 340 m/s. D 173 Interference of Light 3 y m 2 m P S1 m 1 m m0 O m S2 m x 1 m 2 3 Figure 6 Bright fringe surfaces for two coherent point sources. 16, 17. The entire bandwidth 1¢n = n2 of the signal was used. This may be expressed by B = kh¿ (24) where k is the appropriate proportionality constant. Then y = A sin w0 = y0 from which the required initial phase angle w0 can be calculated as w0 = sin-1 a y0 b A The waveforms in Eqs. (See Example 1.). However, the radiation received at the earth's surface is modified by absorption in the earth's atmosphere. Radial keratotomy introduces radial cuts in the cornea of the myopic eyeball (see Figure 8). Then, or m = m¿ + 1N + 12 2d2 2d2 + N + 1 l¿ l¿ (13) By subtracting Eq. (11) from Eq. (12) and by writing the mirror movement of ¢ d2 - d1 , we find l¿ - l = 1l¿ 2e¢ (13) Now since l and l¿ are very close, the wavelength difference of the two unresolved components can be approximated by ¢l = l2 2e¢ (14) This technique is often employed in an optics laboratory course to measure the wavelength difference of 6 Å between the two components of the yellow "line" of sodium. von Fraunhofer. As before, the average phase at P of the light from each successive zone advances by a half-period, or p. Sources at room temperature (293 K) emit electromagnetic radiation with a peak wavelength in the infrared region, lmax = 9890 nm. (a) c = 43.3°, p = 55.6°, p' = 34.4° (b) R = 3.47%, T = 96.53%; R = 8.21%, T = 91.79% (c) R = 3.47%, T = 96.53%; R = 0.67%, T = 99.33% (d) 0, 0, , 2.43 rad, 2.65 rad, 16. Variations in V therefore modify the polarization state of the emergent light, rendering it elliptical, in general, with an xcomponent that can be transmitted by the analyzer. It may be useful to research and then summarize the solution to this problem. For n2 = 1.6 [curve (b)], the spectral response of the double layer, while more reflective, is flatter over the visible spectrum. The optical axis for a spherical lens is an axis of symmetry since rotation of the lens through an arbitrary angle about the optical axis leaves the lens looking just as it did before the rotation. For the approximation, assume the path difference between the two beams is much smaller than s, so that we are looking at the inner zones of the hologram. Evidently an experimental determination of this slit separation could be used to deduce the size s of the extended source. Since the energy of the incident beam is equally divided between Es and Ep components, it also follows that the refracted beam is partially polarized and richer in the Ep component. The intersection of the two rays (extended backward) determines the image point I conjugate to O. The geometric relationship between the angles ui and ut , formed by the representative incident ray AD and refracted ray DL, is Snell's law, as outlined in Figure 4b. Two procedures currently available for corneal sculpting are known as PRK (photorefractive keratectomy) and LASIK (laser in-situ keratomileusis). Pump energy that does not result in laser output inevitably degrades into thermal energy. A general harmonic wave in three-dimensions can be expressed in complex form as B # B c = Aei1k r - vt2 (23) Recall that the physical waveform is described by the real or imaginary part of the complex form.) The partial differential equation satisfied by such three-dimensional waves is a generalization of Eq. (2) in the form 0 2c 0x2 0 2c + 0y2 0 2c + 0z2 = 1 0 2c y2 0t2 (24) as can easily be verified by computing the second partial derivatives of c from Eq. (23). Fourier Optics: An Introduction, 2d ed. For laser sources, these phases would typically be random functions of time that vary on a time scale much longer than an optical period but still shorter than typical detector averaging times. As the angle of incidence increases to grazing incidence 1u = 90°2, both RTE and RTM become unity, although RTM remains quite small until Brewster's angle has been exceeded. Finally, we give a qualitative description of the operation and characteristics of diode lasers. Although Newton often argued forcefully for positing hypotheses that were derived only from observation and experiment, here he himself adopted a particle hypothesis, believing it to be adequately justified by his experience. Upon setting this expression equal to zero, there remains in a(Q), then, only the third-order aberration represented by a term in h1, a1Q2 = -n2 1 h4 n1 1 1 2 1 2 c a + b + a - b d 8 s s R s¿ s¿ R axial object points (18) When h is small enough, the rays are essentially paraxial and the aberration represented by this term may be negligible. The shift may occur in a polar molecule, like H2O, because the molecule has a permanent electric dipole, that is, the effective centers of its positive and negative charge distributions do not coincide. (a) 82.5%, 84.7%, 90.9% (b) 82.5%, 80.1%, 69.5% (b) 41 nm 19. Determine (a) radii of curvature of the lens surfaces; (b) individual focal lengths for the Fraunhofer D line; (c) the overall focal lengths of the lens for the Fraunhofer D, C, and F lines. In the same way, the acoustic wave with B wave vector kS can be considered a flux of quantized particles called B phonons, each of energy UvS and momentum UkS . If the second term in the square brackets is accordingly neglected compared to the first, Eq. (15) describes zones with equal areas (independent of n), given by Sn c pr0œ d r0l 1r0 + r0œ 2 (16) The existence of the second term in Eq. (15), however small, indicates increases in zonal areas with n and corresponding small increases in the successive terms of Eq. (14). The irradiance over the screen turns out to be just a product of the irradiance functions in each dimension, or I = I01sinc2 b21sinc2 a2 (18) 276 Chapter 11 Fraunhofer Diffraction In calculating this result, the single integration over one dimension of the slit is replaced by a double integration over both dimensions of the aperture. The beam diverging from the source slit encounters a second slit 0.5 mm wide at a distance of 30 cm. Three systems are shown characterized. (a) f = 23. Five additional polarizers of this type are placed between the two just described, with their transmission axes set at 15°, 30°, 45°, 60°, and 75°, in that order, with the 15°-angle polarizer adjacent to the 0° polarizer, and so on. Find the quality factor Q of this Fabry-Perot cavity. While the more proximate near point might serve as an advantage, the lessremote far point is a distinct disadvantage and calls for correction. A photon should be thought of as a quantum of energy associated with the entire electromagnetic field. In deriving these equations, it was necessary to assume paraxial rays, that is, rays both near to the optical axis and making small angles with it. Rays associated with the nodal points and principal planes are also shown. Compare this result with the similar result given in Eq. (43) for the ring cavity and account for the differences between the two results. The law of energy conservation suggests that there can be a strong exchange of energy between an electromagnetic wave of frequency n0 and matter only when some of the constituents of the matter have allowed energies En and EM Em such that En - Em = EEM = hn0 .1 In such a case, we say that n + 1 - En the electromagnetic field is resonant with the En to Em transition of the atom or molecule. 362 Chapter 15 Production of Polarized Light OA 偏 E E偏 a b P E a OA Surface (a) S E k O Plane wavefront (b) Figure 13 (a) Creation of an elliptical Huygens' wavelet by the extraordinary ray. In Figure 16a, a plane wave is reflected from an ideal (infinite) plane mirror. In a farsighted eye, the natural converging power of the eye is not strong enough, and additional converging power must be added in the form of spectacles with a converging lens. Situations exist where the actual path taken by a light ray may represent a maximum time or even one of many possible paths, all requiring equal time. Laurance. 1967: 238. In every other case, sin u = 0 for u = np, n = ; 1, ; 2, Á , and so g1v2 = 0 when v = v0 ; 2np t0 (14) As v increases (or decreases) from v0 then, g1v2 passes periodically through zero. (a) Four-step energy cycle for a laser atom involved in the creation of laser photons. As illustrated in Figure 6, when I = IS the gain coefficient is reduced by a factor of 2 from its small-signal value. (b) Quarter-half-quarter wavelength layers. 4 RESOLUTION OF A GRATING Increased dispersion or spread of wavelengths does not by itself make neighboring wavelengths appear more distinctly, unless the peaks are themselves sharp enough. Such large reflecting telescopes are usually employed to examine very faint astronomical objects and use the integrating power of photographic plates, exposed over long time intervals, in observations. One such zone (ABCD) is shown. In Eqs. Crystals with thicknesses equal to their coherence length are impractically small. Such rays incident on the second surface can then be refracted again to form an image. A total of 256 data points is fed to the computer for Fourier-transform analysis. Central to his explanation was the conception of light as a stream of light quanta whose energy is related to frequency by Planck's equation (1). That is, the irradiance transmitted through a Fabry-Perot is measured as a function of the length of the cavity. Let us consider the direction to the right across the page to be the positive z-direction. With the definition of the real, positive number, a K kt sin2 u - 1 B n2 the transmitted wave may be expressed as B # B Et = E0tei1kt r - vt2 = E0te -ivte -ixkt sin u>ne -af z f The last factor on the right-hand side of this relation describes an exponential decrease in the amplitude of the wave as it enters the medium of lesser refractive index along the negative z-direction. We assume that lasing action occurs only in the counterclockwise direction around the ring. In either case, then, m = - s¿ s (30) Further ray-diagram examples for a train of two lenses are illustrated in Figure 23 and a calculation involving image formation in two lenses is given in Example 3. The holes S1 and S2 are usually slits, with the long dimensions extending into the page. However, as noted, in a Q-switched system the cavity is left in the high-loss state for a time long enough to allow the population inversion to build to a large value. In this arrangement, the light incident on the QWP is divided equally between fast and slow axes. By producing a hologram that restricts the possible angular views of the subject to one through a horizontal slit, the confusion of images is reduced. y FA x Unpolarized light SA Figure 9 Operation of a phase retarder. He was impressed, for example, 2 A more in-depth historical account may be found, for example, in Vasco Ronchi, The Nature of Light (Cambridge: Harvard University Press, 1970). The top of the comatic circle is formed by rays 1 and 2; the bottom by rays 3 and 4. An infinite variety of shapes may be synthesized in this way. Surface scratches or irregularities, as well as surface dust, moisture, or grease, become sources of loss that rapidly diminish light energy. (See Figure 2.) In fiber-optics systems, the carrier source is typically either a light-emitting diode (LED) or a laser diode (LD). A plot of spectral solar irradiance is given in Figure 4. The spherical aberration of a single, spherical refracting surface is given in Eq. (18). In most cases, a time average of the power delivered per unit area is all that is required. For light diffracted in the direction um , the net path difference of the two waves is ¢ 1 - ¢ 2 . Two important homogeneous broadening mechanisms are called lifetime broadening and pressure broadening. (48), (50), and (51), me = Dex 1 = M Dobj so that Dex = Dobj M (52) Thus, the diameter of the bundle of parallel rays filling the objective lens is greater by a factor of M than the diameter of the bundle of rays that pass through the exit pupil. The apertures dealt with are often purposely inserted into an optical system to achieve various practical purposes. Since these sources are not coherent, interference is sustained only between pairs of reflected rays originating from the same source. Then, it follows that 8phn30 A 21 = B21 c3 (8) B12 = B21 (9) and Thus we have derived the relations between the Einstein A and B coefficients by considering a thermal equilibrium situation. New York: Cambridge University Press, 1990. An object OP, 3 cm high is located 18 cm to the left of L1 . The transmitted light is then monitored by a light detector placed in the second focal plane of L4 , labeled Output in Figure 7. Consider the cases represented in Figure 10. Tech. The inset shows the relationship of wave vectors required by momentum conservation when the acoustic wave has the propagation direction indicated. If the corresponding refractive indices are n1 and n2 , the figure implies that n1 7 n2 . The finite lifetime of the atomic levels is due both to the fundamental process of spontaneous emission and to transitions induced by inelastic collisions with other atoms. Field of View: Field Stops and Windows In describing the limitations of a cone of rays from an axial object point, we have seen that entrance and exit pupils are related to the aperture stop and so govern the brightness of the image. photons. Thus, for example, multiplying the vector representing left-circularly polarized light by eip>2 = i, 1 i ic d = c d i -1 produces an alternate form of the vector. Narrow band-pass filters that behave like Fabry-Perot etalons can be fabricated by separating two dielectric-mirror, multilayer structures with a spacer of, say, MgF2 film. The pattern reveals that the fourth-order interference maxima are missing from the pattern. Surface imperfections or internal variations in refractive index show up as a distortion of the fringe pattern. Example 1 illustrates the manner in which the cavity structure determines the parameters and behavior of a Gaussian beam generated in the cavity. The use of an etalon to limit a laser to single mode operation is explored in Example 5. These rays take a piecewise spiral path through the fiber. 20 Find expressions for the fraction of the total power in a beam of spot size w(z) that is transmitted through a circular aperture, centered on the beam, of radius a for a (a) TEM00 , (b) TEM01 , (c) TEM11 , and (d) TEM02 beam. The reflection coefficient for the case of internal reflection is shown in Figure 5 with n = 1>1.50, as when light encounters a glass/air interface from the glass side. 12 In writing Eq. (3) we neglected to include a contribution due to the magnetic force on the electron. Through successive layers of neurons (bipolar cells), the electrical signals induced by the chemical changes in the photoreceptors are led out of the back of the eye along axons, which are the fibers of the optic nerve. The wavelength is l. Imagine now that the objects S1 and S2 are brought closer together. We have assumed that mirrors M1 and M2 are precisely perpendicular as shown in Figure 1a, or, what amounts to the same thing, precisely parallel in the equivalent optical system of Figure 1b. What is the optical saturation power for this detector? Now, by way of summary, we turn our attention to the identification of some of the common lasers in existence today and to the parameters that distinguish them from one another. These results are all displayed in Figure 6, where the origin of the frequency spectrum is chosen at its point of symmetry, v = v0 . Materials used in electro-optic applications typically have second-order nonlinear susceptibility constants x2 in the range of 10-10 m>V to 10-13 m>V, and third-order nonlinear susceptibilities in the range of 10-17 m2>V2 to 10-22 m2>V2. The aberrations have been studied and classified by the German mathematician Ludwig von Seidel and are referred to as third-order or Seidel aberrations. All surfaces have a radius of curvature of magnitude 20 cm. 26 Three thin lenses of focal lengths 10 cm, 20 cm, and - 40 cm are placed in contact to form a single compound lens. In each case, two or more individual coherent beams of light, originating from a single source and separated by amplitude or wavefront division, were brought together again to interfere. 13 Determine the maximum reflectance in the center of the visible spectrum for a high-reflectance stack of high-low index double layers formed using nL = 1.38 and nH = 2.6 on a substrate of index 1.52. A pulsed laser delivers bursts of radiation with durations (pulse widths) as small as a few femtoseconds. Such a periodic structure could be constructed by slicing a crystal into many thin slabs, each having a width equal to LC and then placing the slabs back together in a manner such that each slab is rotated 180° relative to its neighbors. ⵯf 2p ⵯf p/4 ⵯf ⱖp/4 7p/4 ⵯf p/2 ⵯf ⱖp/2 3p/2 ⵯf 3p/4 ⵯf ⱖ3p/4 5p/4 ⵯf p ⵯf p 337 Matrix Treatment of Polarization Now suppose E0x = E0y = A and Ex leads Ey by p>2. A birefringent crystal can be cut and polished to produce polarizing elements in which the OA may have any desired orientation relative to the incident light. What is the overall magnification of the microscope when an eyepiece rated at 10* is used? A further classification of diffraction effects arises from the mathematical approximations possible when calculating the resultant fields. As an example, consider an optical system that consists of two thin lenses in air, separated by a distance L, as shown in Figure 13. Equation (15) now gives normal incidence: ub = 1 2 sin-1 a ml b a (17) Example 3 a. The problem depicted in Figure 10 is to determine the location / of the external beam waist and its spot size w0 . Thus a reticle, the field stop, and field lens are all essentially in the "same plane." A disadvantage of this arrangement is that the surface of the lens is then also in focus, including dust and smudges. Since no light source can be precisely Dispersion in fused quartz Refractive index versus wavelength 1.475 1.470 Refractive index 1.465 1.460 1.455 1.450 1.445 1.440 Figure 11 Dispersion in fused quartz. What is the normal reflectance produced? To determine elements a and c, let the same polarizer operate on horizontally polarized light. The remarkable adaptivity of the eye can be traced, in fact, to the particular photosensitivity of the rods and cones in the retina of the eye. Terms proportional to this expression, therefore, vanish, by Fermat's principle. If extreme points are separated by an amount s 6 rl>/, then fringe definition is assured. Thus, dEp = a EL ds i1kr - vt2 be r (1) where r is the optical-path length from the interval ds to the point P. On the other hand, control over groove profile, which affects the blazing and thus the efficiency of the grating, is not easily achieved. In each case, the irradiance input into the system is 1 W>cm2. 139 Properties of Lasers The following brief survey of nonlaser sources of light is not intended to be comprehensive; rather it is intended to serve as a backdrop for the discussion of laser light that follows in subsequent sections. For angles such that sin u 7 n, when TIR occurs, cos ut becomes purely imaginary and we can write cos ut = i sin2 u - 1 B n2 505 Fresnel Equations Thus the exponential factor B kt # Br = - ktx sin u sin2 u sin u sin2 u ƒ ƒ 1 = k x z - 1 - iktz + ik t t n n B n2 B n2 In writing the last equality we have noted that, for the situation depicted in Figure 1, the transmitted wave exists in the region for which z 6 0, and so in this region z = - ƒ z ƒ . As an example, consider the Fourier analysis of the square wave shown in Figure 2 and represented over a period symmetric with the origin by 0, f1t2 = c 1, 0, - T>2 6 t 6 - T>4 - T>4 6 t 6 T>4 T>4 6 t 6 T>2 226 Chapter 9 Coherence f (t) Figure 2 T 2 T 4 T 4 t T 2 T Square wave. The first case deals with the superposition of harmonic waves of differing amplitudes and phases but with the same frequency. Here k is the propagation vector whose magnitude is related to wave speed by k = v>y. If the pulse moves to the left, the sign of y must be reversed, so that we may write y = f1x ; yt2 (1) as the general form of a traveling wave. The analysis leading to Eq. (22) holds as well for the four-level gain medium being presently considered. p Phase shift on reflection f 3p/4 p/2 TM p/4 0 up 33.7 p/4 TE p/2 3p/4 Figure 6 Phase shift f on reflection of the electric field for internally reflected rays, with n = n1>n2 = 1>1.5. uc 41.8 p Internal reflection (glass-to-air) 10 20 30 40 50 60 Angle of incidence u 70 80 90 It happens that the relative phase shift fTE - fTM is about - 3p>4 at an angle of incidence near 53°. In practice, this is easily accomplished by placing a source in the focal plane of a positive lens or by simply using a laser beam with a small divergence angle as the source. First, it does not take into account the obliquity factor, which attenuates the diffracted waves according to their direction, as described earlier. Inserting it into Eq. (59), v2p 2 n = 1 - (61) v2 + ivg The plasma frequency turns out to be a critical frequency whose value determines whether the refractive index is real or imaginary. When viewed at u = 0°, along the normal to the surface, a certain maximum A A A A r A A A A A A A A A A Figure 3 Illustration of the inverse-square law. It is often referred to as the ABCD propagation law for Gaussian laser beams. The complex vector amplitudes are given by ' E0 1 E0ᶜ = a b c d 2 i ' E0 1 E0ᴾ = a b c d 2 -i and (7) corresponding to the Jones vectors for left- and right-circularly polarized modes. 332 Chapter 13 Fresnel Diffraction 11 For an incident plane wavefront, show that the areas of the Fresnel half-period zones relative to an observation point at distance x from the wavefront are approximately constant and equal to plx. We shall use the ABCD propagation law, Eq. (43), which involves the ABCD matrix from transverse plane Z1 to transverse plane Z2 . Value given is for the relaxed eye. Peter K. 33 What is the band-gap energy of an AlGaAs semiconductor used in a laser diode device that emits light of wavelength 800 nm? Thus the coherence length is the average length of light beam along which the phase of the wave remains unchanged. There we added the amplitudes of all the individual reflected or transmitted beams to find the resultant reflectance or transmittance. This integration is, in general, not easy to carry out for a given aperture. Diode Laser Operating Characteristics Important favorable characteristics of diode lasers are that they are relatively inexpensive, are small and efficient, and can be engineered to have a variety of wavelengths of interest in many applications. Let the angle of refraction be the angle u2 . A little inspection of these equations shows that the Nth such reflected wave can be written as EN = 1tt¿r¿ 12N - 32E02ei[vt - 1N - 12d] (45) 187 Interference of Light a form that holds good for all but E1 , which never traverses the plate. Ray A entering the left face of the fiber is refracted there and transmitted to point C on the fiber surface where it is partially refracted out of the fiber and partially reflected internally. (2) 1 km P1 P2 5 Since rays that strike the fiber wall at smaller angles of incidence travel a greater distance through the same axial length L of the absorbing medium, a is also a function of the angle of incidence. If the extended source of Figure 15a is the sky and white light is incident at some angle on a film of variable thickness, as in Figure 16, the film 181 Interference of Light may appear in a variety of colors, like an oil slick after a rain. On the other hand, very intense radiation may be visible beyond the limits of the CIE curve. A reflective metallic coating is usually added to the grating by vacuum evaporation. B a. The shift in charge distribution may also occur in nonpolar molecules, such as O2 , in which positive and negative charge distributions normally have the same effective center. This means that in place of the expansions sin w = w - w5 w3 + - Á 3! 5! cos w = 1 - w2 w4 + + Á 2! 4! and (8) we consider the first terms only and write sin w w and cos w 1 (9) relations that can be accurate enough if the angle w is small enough.4 This approximation leads to first-order, or Gaussian, optics, after Karl Friedrich Gauss, who in 1841 developed the foundations of the subject. The linear dispersion of the instrument is 20 Å/mm and an exit slit of 200 mm is used. Available eyepieces have eye reliefs in the range of 6 to 26 mm. One of the most monochromatic gas-discharge sources is a gas of the krypton 86 isotope, whose orange emission line at 606 nm has a line width of only 0.00047 nm. Determine its average irradiance and the amplitude of its E and B fields. Now, if we assume the point spread function to be space-invariant (independent of object point coordinates), it can only depend on the relative displacement of conjugate points: G1x, y, X, Y2 = G1X - x, Y - y2 Further, if the light from the object plane is incoherent, irradiances add,2 and we can write for the irradiance at the image point (X, Y) due to all object points (x, y): Ii1X, Y2 = 5 image irradiance I01x, y2 G1X - x, Y - y2 dx dy O5 5 object irradiance (31) point spread function The integral in Eq. (31) is called the convolution3 of the functions I0 and G, usually abbreviated by Ii = I0 z G (32) Suppose that we calculate the Fourier transform of each of these functions, represented by Ḉ1I02, Ḉ1Ii2, and Ḉ1G2. These results, derived here for the case of two wave components, hold in general for a number of waves with a narrow range of frequencies. 54, No. 17 (2001). Light wavelengths range from 380 nm (violet) to 770 nm (red). 11 RAY TRACING The assumption of paraxial rays greatly simplifies the description of the progress of rays of light through an optical system, because trigonometric terms do not appear in the equations. 4 COMA Coma, represented by the term 1C31h¿r3 cos u, is an off-axial aberration 1h¿ Z 02 that is not symmetrical about the optical axis 1cos u Z constant2 and increases rapidly as the third power of the lens aperture. This becomes clearer if Eq. (43) is written in the equivalent form, r = eipr¿. (Recall that "small signal" is code for "set I = 0.") d. (20) and (21) into the Eqs. Upon further lowering the microscope barrel by 1.87 mm, a focused image of the scratch is seen again. Consequently, objects located closer than the hyperopic near point would be out of focus, even with full accommodation. 5 VISION CORRECTION WITH EXTERNAL LENSES The errors of refraction of the eye lead to four well-known defects in vision: myopia (nearsightedness), hyperopia (farsightedness), presbyopia, and astigmatism. An echelle grating is a coarsely pitched grating designed to achieve high resolution by operating in high orders. Using the polar form, ' ' ' ''... z z = 1 ƒ z ƒ eiu2 1 ƒ z ƒ e-iu2 = ƒ z ƒ 2 ⱕi (17) Finally, it will be helpful to list the values of eiu, using Euler's formula, Eq. (13), for frequently occurring special cases. Optical fibers play an increasingly important role in a wide array of optical systems. Therefore, the Boltzmann distribution of Eq. (4) can be used to write P2>P1 = N2>N1 = e-1E2 - E12>kBT 6 1 146 Chapter 6 Properties of Lasers Therefore, stimulated absorption will occur more often than stimulated emission in an assembly of atoms in thermal equilibrium with its environment. This adjustment of pupil diameter (from 8 mm down to 2 mm) cannot of itself account for the enormous range of intensities processed by the eye. For example, in the case of an 1 See, for example, E. Currently, new laser applications are discovered almost weekly. Solution The N. When this occurs, the irradiance no longer grows and so the population inversion maintains a steady value. If the diameters of these circles are small enough, the resultant image is still acceptable. According to Eq. (32), depth of field is greater for smaller apertures (larger f-numbers), shorter focal lengths, and longer shooting distances. In practice, this condition is only approximately met, and we speak of partial coherence. J. The finished hologram can be erased by heating and the thermoplastic recording material can be reused hundreds of times. Englewood Cliffs, NJ: Prentice-Hall, 1995. Then, Eqs. The device consists of three essential elements: an external energy source or pump, a gain medium, and an optical cavity, or resonator. For 3-cm microwaves, for example, the skin depth in copper, with conductivity of 5.8 * 107> Æ-m, is only about 6.6 * 10-5 cm. Such a point, U, is shown in part (b) of the figure, the same optical system as (a), but redrawn for clarity. Viewed in another way, Eq. (4) requires an increase in the angular separation ¢u of a given small fringe interval ¢m as the mirror spacing d becomes smaller, since taking the differential of Eq. (4) leads to ƒ ¢u ƒ = l¢m 2d sin u 1 This conclusion assumes real beam-splitter transmission coefficients. Since dispersion is limited by the glass, prism resolving power might be improved by increasing the base b. Where will sunlight be focused by the crystal ball? Such a gas only emits and absorbs light of particular, nearly discrete, energies. 365 Production of Polarized Light means that if one views white light through an arrangement like that of Figure 17, each wavelength is rotated to a slightly different degree. Bell, Robert John. What is the irradiance at the detector relative to the irradiance there for an unobstructed wavefront? If the aperture is square, the blurs are rectangular in shape. 5 cm 26. Locate the exit pupil. A source slit is parallel to the intersection between the mirrors and 50 cm 190 Chapter 7 Interference of Light away. In the case of circular zones, Figure 4b, the corresponding resultant phasor has a phase angle of p>2 and the corresponding point, T, would fall on the vertical axis. So gain media with larger bandwidths can be used to form narrower mode-locked pulses. Adding a good narrow-band filter further reduces the power but improves the temporal coherence. Point P falls on such a ring, for example, if the optical path difference OP - OX is an integral number of wavelengths, ensuring that the reference beam of plane wavefront light arrives at P in step with the scattered subject beam of light. 21 Consider the CO2 transition described in Example 4. The fringes of equal inclination just described are not possible if the source is a point or is very small, since every ray of light from the source to the film must, in that case, arrive at a different angle of incidence (Figure 14). Let the object in the aperture plane be illuminated uniformly by light of unit amplitude, and let its transmission function be described by E11x, y2. Each ray refracts twice through the lens, once at each surface. 4 CONSERVATION OF ENERGY To conserve energy, at a given boundary, it must be true that the power incident on the boundary be equal to the sum of the power reflected at that boundary and the power transmitted through the boundary. In fact, in his original work, Gabor proposed reconstruction of an electron-wave hologram with optical wavelengths in an effort to improve the resolution of electron microscopes. 16 A telephoto lens consists of a combination of two thin lenses having focal lengths of +20 cm and -8 cm, respectively. If now the OA is situated so that it makes an arbitrary angle with respect to the beam direction, as in Figure 12, the light experiences double refraction5; that is, two refracted beams emerge, labeled the ordinary and extraordinary rays.

1.33 - 1 1 + = 30 s¿ 1 5 giving s¿ 1 = + 40 cm. In this case, Eq. (62) reduces to 0p>0z = i>q, the defining equation for p obtained earlier. Most cameras are equipped with a depth-of-field scale from which values of s1 and s2 can be read, once the object distance and aperture are selected. Because the orientation of the surface curvature does not change in such a rotation, its optical behavior remains unchanged. The other ray is an arbitrary ray incident at P and refracting there according to Snell's law, n1 sin u1 = n2 sin u2 (17) The two refracted rays appear to emerge from their common intersection, the image point I. The effect of Energy>photon 3.58 * 10-19 J addition or removal of a single photon would perhaps be noticeable. This correction is handled by the obliquity factor to be discussed presently. What, approximately, is the irradiance at the point? Calculate the energy difference, in eV and in J, between the ground state energy E1 and the first excited state energy E2 of the hydrogen atom. Sunlight and Skylight Daylight is a combination of sunlight and skylight. By what factor is this fiber an improvement over a step-index fiber with n1 = 1.46 and n2 = 1.44? The first is included under the general heading of optical data imaging and processing and the second, Fourier-transform spectroscopy. With these modifications, Eq. 2 can be rewritten as dEP = a ELds i1kr0 - vt2 iks sin u be e r0 (3) The total electric field at the point P is found by integrating over the width of the slit. Reflecting or refracting surfaces that form perfect images are called Cartesian surfaces. RTE does not go to zero under this condition, so reflected light contains only the TE mode and is linearly polarized, with RTE = 15%. If the values of the Fresnel integrals are plotted against the variable y, as real and imaginary coordinates on the complex plane, the resulting graph is the Cornu spiral (Figure 12). This process produces the population inversion required for effective amplification via stimulated emission of radiation. The image formed by the second surface is then the final image due to the action of the composite thick lens. A pair of plastic safety goggles inserted between crossed polarizers shows a higher density of color changes in those regions under greater strain, because the difference in refractive indices changes most rapidly in such regions. Xenon Fluoride Xenon Chloride Krypton Fluoride Gas, excimer Argon Fluoride Nitrogen Gas, molecular Carbon Dioxide Krypton Gas, ion Argon Helium Cadmium Gas, atomic Helium Neon Gain medium short-pulse electric discharge short-pulse electric discharge short-pulse electric discharge electric discharge electric discharge electric discharge electric discharge Pump type 351 nm 308 nm 248 nm 193 nm 337.1 nm 10.6 mm several from 350– 530 nm, main lines: 488 nm, 514.5 nm several from 350–800 nm, main line: 647.1 nm 325 nm, 441.6 nm, others 0.6328 mm, others Wavelength up to 30 W (average) up to 150 W (average) up to 100 W (average) up to 50 W (average) 1–300 mW (average) 3 W–20 kW 5 mW–6 W 2 mW–20 W 5–150 mW 0.1–50 mW Power/Energy TABLE 1 LASER PARAMETERS FOR SEVERAL COMMON LASERS pulsed pulsed pulsed pulsed cw or long pulse pulsed cw (or modelocked) cw (or modelocked) cw cw Output type 2 * 4 – 25 * 30 mm (rectangular) 2 * 4 – 25 * 30 mm (rectangular) 2 * 4 – 25 * 30 mm (rectangular) 2 * 3 – 6 * 30 mm (rectangular) 3–50 mm 0.6–2 mm 0.2–2 mm 0.5–2.5 mm Beam diameter 2–6 mrad 2–6 mrad 2–6 mrad 2–6 mrad 1–3 * 7 mrad 1–3 mrad 0.4–1.5 mrad 0.4–1.5 mrad 1–3 mrad 0.5–3 mrad Beam divergence 62% 62.5% 62% 61% 60.1% 5–15% 60.05% 60.1% 60.1% 60.1% Efficiency air or water air or water air or water air or water flowing gas flowing gas water or forced air water or forced air air Cooling 159 flashlamp, diode laser, doubled Nd:YAG flashlamp, diode laser Ti-sapphire InGaAsP Semiconductor Lasers GaAs, GaAlAs electric current, optical pumping electric current, optical pumping flashlamp Alexandrite Erbium:Fiber flashlamp flashlamp, arc lamp, diode laser other lasers, flashlamp Pump type Nd:glass Solid-State Nd:YAG Liquid Various Dyes Gain medium TABLE 1 Continued 1100–1600 nm, composition dependent 780–900 nm, composition dependent 1.55 mm tunable, 660–1000 nm 1 mW to several watts, diode arrays up to 100 kW 1 mW to ' 1 W 1–100 W 0.1–100 J per pulse 6 100 W average power '2 W average power 1.06 mm tunable, 700–818 nm up to 10 kW (average) 20 mW–1W (average) Power/Energy 1.064 mm tunable 300–1000 nm Wavelength cw or pulsed cw or pulsed cw or pulsed cw or (ultrashort) pulsed cw or pulsed pulsed cw or pulsed cw or (ultrashort) pulsed Output type N/A (diverges too rapidly) N/A (diverges too rapidly) a few mm a few mm a few mm 3–25 mm 0.7–10 mm 1–20 mm Beam diameter 200 * 600 mrad (oval in shape) 200 * 600 mrad (oval in shape) a few mrad a few mrad a few mrad 3–10 mrad 0.3–25 mrad 0.3–2 mrad Beam divergence 1–20% 1–50% comparable to Nd: YAG comparable to Nd: YAG 0.5% 0.1–2% (5–8%, diode pumped) 1–5% 1–20% Efficiency air, heat sink air, heat sink air, heat sink air air or water air or water air or water water air air or water dye flow or water Cooling 160 Chapter 6 161 Properties of Lasers PROBLEMS 1 The Lyman series in the line spectra of atomic hydrogen is the name for the light emitted from transitions from excited states to the n = 1 hydrogen ground state. Equations (2) and (3) then become ' Ex = E0xe -ivt y P A t0 Ey 0 Ex ⩽A (a) y P A x ' Ey = E0ye -i1vt - e2 The negative sign before e indicates a lag e in the y-vibration relative to the xvibration. Gerrard, A., and J. The high degree of directionality of a single-mode laser beam is due to the geometrical design of the laser cavity and to the fact that the stimulated emission process produces twin 155 Properties of Lasers Pinhole (a) (b) Filter (c) (d) Figure 18 A tungsten lamp requires a pinhole and filter to produce partially coherent light. for 20/100; 0.262 in. Notice that the angles A and B and the two right angles formed by the normals with the prism sides constitute such a quadrilateral. Determine the proper blaze angle. For optical wavelengths, the conduction paths analogous to the grid wires must be much closer together. Assume a film refractive index of 1.6. a. Then n = n1k2, and dyp dk = d c - c dn a b = 2a b n dk n dk When incorporated into Eq. (38), we have an alternate relation between phase and group velocities, yg = yp c 1 - k dn a bd n dk (39) Again, using k = 2p>l and dk = - 12p>l22 dl, Eq. (39) can be reformulated as yg = yp c 1 + l dn a bd n dl (40) In regions of normal dispersion, dn>dl 6 0 and yg 6 yp . Solution Substituting directly into Eq. (53), we get R = c 11>1.48211.46>2.35212 - 1 11>1.48211.46>2.35212 + 1 d 2 or R = 99.1%. Optical Information Processing, Fundamentals. Calculator and watch displays often operate with ambient light. The intervening space is filled with oil of refractive index 1.65. In arriving at this result, Kirchhoff assumed as boundary conditions that the 1 This derivation requires mathematical ability that is beyond the stated level of this textbook but can be found in many places, for example, Max Born, and Emil Wolf. The useful aperture of this double-beam interferometer is such that all rays striking M1 and M2 will be normal, or nearly so. Enlarge the system to a distance x beyond the hemisphere and find the new system matrix as a function of x. It is interesting to note that the theoretical resolution just determined for a 2-mm-diameter pupil is consistent with the value of 1¿ of arc 129 * 10-5 rad2 used by Snellen to characterize normal visual acuity. Solution Using Eq. (13), we have d = 45° * 60 min>° b = = 2.68 cm VB 10.112 mm>G-cm2 * 9000 G 5 THE ACOUSTO-OPTIC EFFECT Photoelasticity is the change in refractive index of a crystal due to mechanical stress. (Both photos are from M. No light is reflected through these pixels and so they appear dark. When R : q , the spherical surface becomes a plane refracting surface, and s¿ = - a n2 bs n1 (21) where s¿ is the apparent depth determined previously. 11 A hologram is constructed with ultraviolet laser light of 337 nm and viewed in red laser light at 633 nm. Color displays can be made by placing a mask containing an array of red, green, and blue filters arranged in groups of three "subpixels." Controlling the brightness of the light transmitted through the different color subpixels allows for the generation of the complete range of "natural" colors. What is the absorption coefficient for tin, with an imaginary part of the refractive index equal to 5.3 for 589.3-nm light? 6 To determine the refractive index of a transparent plate of glass, a microscope is first focused on a tiny scratch in the upper surface, and the barrel position is recorded. 32 Estimate the diffraction-limited far-field divergence angles of a beam output from the heterojunction laser diode illustrated in Figure 19. Example 3 A 5 cm focal length lens with an f/16 aperture is used to image an object 9 ft away. Indeed, the principles of holography do not depend on the transverse character of the radiation. The collimated beam length is arbitrarily defined as the distance between two symmetrical, transverse planes on either side of the beam waist, the two planes being those in which the spot size w (z) has increased by a factor of 22 over the spot size w0 at the waist. Each wavelength forms its own system of circular fringes according to Eq. (4). (uFF)1 brought to a focus with beam waist w02 located a distance Z2 to the right of the lens. 104 Chapter 4 Wave Equations Here, r represents the perpendicular distance from the line of symmetry to a point on the waveform. Determine the normal reflectance for sodium light of wavelength l0 = 589.3 nm. 102 Chapter 4 Wave Equations Equation 20 can therefore be generalized if the propagation constant, whose magnitude 2p>l has already been determined in Eq. (4), is now considered to beBa vector quantity, pointing in the direction of propagation. How much larger is the image of the person using this telephoto lens? Referring back to Figure 11, it should be evident that both a change in frequency and a change in direction of the acoustic wave cause a change in the direction of the diffracted beam. Neglecting the obliquity factor for small angles u, Eq. (9) represents a spherical wave whose amplitude decreases with distance r. The interference term I12 , in this case, takes the form, 2 2I1I28cos1k1s2 - s12 + f21t2 - f11t229 As stated, for real detectors and for all but those laser sources with state-of-theart frequency stability, the time average in the preceding relation will be zero. 11 You have been asked to design a Snellen eye chart for a test distance of 5 ft. Self-Phase Modulation and Cross-Phase Modulation In order to carry information in a fiber, the irradiance of the signal wave must vary in time at a given point in the fiber. Like X-rays, penetrating gamma rays find use in the medical area, often in the treatment of localized cancers. Semiconducting compounds cadmium sulfide (CdS) and cadmium selenide (CdSe) are often used in the visible and near-infrared regions; farther out in the near-infrared region, the compounds lead sulfide (PbS) (0.8 to 3 mm) and lead selenide (PbSe) (1 to 5 mm) are popular. Show that the relation from part (b) agrees with Eq. (43) only if the survival fraction is close to 1. 452 Chapter 20 Aberration Theory P♣ M O N I P (1) (2) (a) (b) (c) (d) Figure 11 (a) Effect of an aperture stop on the distortion of an image by a lens. At what distance from the objective is a point object viewed by the microscope? This result can be demonstrated by analyzing the Cornu spiral results associated with the slit and wire apertures of Figures 15 and 16. The maximum core index is 1.46 and the cladding index is 1.44. In Figure 4, a sample discrete set of coefficients, as might be calculated from Eq. (6), is shown together with a continuous distribution approximated by the coefficients, such as might result from Eq. (8). The nature of the beam inside the laser cavity and its characteristics outside the cavity are not discussed in detail in this chapter. In the Y-direction these are given by kY = kY f (21) Since the transmission function for the Ronchi ruling is a periodic square function, it is represented by a discrete set of frequencies in a Fourier series rather than by a continuous distribution of frequencies in a Fourier integral. Of this total power, 99.95% is wasted as heat energy. (a) 0.856 cm (b) 6.63 μm 7. In this case, the line image AB is longer than the axial length of the lens, CL. The degree of coherence can be observed by examining the interference fringe contrast in an amplitude-splitting instrument, such as the Michelson interferometer. Furthermore, it is the EnP of the system because it is the first element encountered by the light from the object. Franken, A. Due to the rather intricate laminar structure of fibrous tissue, the refractive index of the lens is not homogeneous. Since not all human eyes are identical, a standard response has been determined by the International Commission on Illumination (CIE) and is reproduced in Figure 2. The use of a symmetrical placement of lenses, or groups of lenses, with respect to the aperture is often a distinctive feature of such lens designs. Ch. 20. Both are included within a branch of physics referred to generally as Fourier optics, in which the Fourier transform, convolution, and correlation are central concepts of mathematical analysis. However, this technique soon requires impractically large and heavy prisms. 311 Fresnel Diffraction wave function and its gradient are zero directly behind the opaque parts of the aperture, and that within the opening itself, they have the same value as they would in the absence of the aperture. The resultant wave may be written as a sum of the individual waves. It follows that the ExP is also conjugate with the EnP. Sketch the orientation of the OA of the two plates. The upper energy band is the conduction band and the lower energy band is the valence band. An astigmatic eye, for example, while it possesses predominantly spherical optics, might have a cylindrical axis component whose axis could be horizontal, vertical, or some angle in between. Thus, light amplification occurs during each pass through the gain medium. In such a case, the field radiated by the atom is composed of some photons originating from the spontaneous emission process and some photons originating from the stimulated emission process. Interpret the result. 5 A ray of light makes an angle of incidence of 45° at the center of the top surface of a transparent cube of index 1.414. In such cases, the index is "stepped down" consistently from substrate to ambient. Multiple reflections in the region of l0 increase the total reflected intensity and the quarter-wave stack performs as an efficient mirror. A fringe pattern characterizing the surface contour is observed using He-Ne light of wavelength 632.8 nm. Mode spacings in a typical laser system using an etalon for mode suppression are shown in Figure 16b. Following convention, we call w(z) the spot size of the beam. Linearly polarized E-vector at 30 with x-axis y y E QWP SA Figure 12 x SA along x-axis Problem 10. That is, the nonlinear interaction can convert energy from the second harmonic wave into the fundamental wave. The double slit studied previously constitutes an obstruction to a wavefront in which light is blocked everywhere except at the two apertures. The refracted beam reflects again at the film-substrate interface B and leaves the film at C, in the same direction as the beam reflected at A. The added complexity does not pose a problem for the computer, once the ray-tracing program is written. Using Eq. (41), nfsr = c. (a) 0.633, 1.898, 3.164 mm (b) 0.50 mm (c) 12.57, 1 37.70, and 62.83 cycles/mm (d) 1: 19 : 25 2. 12 The small angle u between two plane, adjacent reflecting surfaces is determined by examining the interference fringes produced in a Fresnel mirror experiment. If instead B is transverse to the plane of incidence, a case to be considered later, the mode is a transverse magnetic (TM) mode. (b) Use of the Cornu spiral in analyzing straight-edge diffraction. Consistent with his conception, Huygens imagined each point of a propagating disturbance as capable of originating new pulses that contributed to the disturbance an instant later. Arquimedes. Since most of us, at one time or another, are required to read eye charts in a vision test, we limit our discussion of visual acuity to resolving powers associated with minimum legible resolution. Find the cardinal points for the lens and the position and size of the image formed. Some improvement results when the middle layer is of l>2 thickness, as in Figure 6b and curve (b) of Figure 7. The functions f(x) and g(k) are said to be a Fourier-transform pair. 8 Write a computer program that will determine Ey-values of elliptically polarized light from the equation for the ellipse, Eq. (12), with input constants A, B, and C and variable input parameter Ex . Thus we seek solutions to the more tractable equation 0 2U 0U 0 2U = 0 + + 2ik 2 2 0z 0x 0y (9) 585 Characteristics of Laser Beams Equation (9) is a nontrivial partial differential equation with complex terms. Performance parameters of practical interest are then developed in discussions of the spectral range, dispersion, resolution, and blaze of a grating. (b) Image of a square grid by a positive lens. The phase of rTE may be investigated by expressing Eq. (34) in complex polar form, as rTE = e -ia = e -i12a2 eia where tan a = 2sin2 u - n2>cos u. Determine the beam divergence angle uFF for this laser. As explained in the previous section, amplification of a light wave or photon radiation field will occur only in a medium that exhibits a population inversion between two energy levels. Screen 630 nm Wire 0.37 mm S 3m 2m Figure 24 19 Calculate the relative irradiance (compared to the unobstructed irradiance) on the optic axis due to a double-slit aperture that is both 10 cm from a point source of monochromatic light (546 nm) and 10 cm from the observation screen. The light incident on the grating is rendered parallel by a primary slit and collimating lens. When the effect is enhanced by using an array of such junctions in series, the device is called a thermopile (Figure 1b). Equation (22) becomes m = - n1 1 1121 + 402 = -1 11.3321 + 302 R 5 n2 1.33 RI RO1 40 30 (a) n1 1 n2 1.33 n1 1 s2 9 RI2 RO1 Figure 20 Example of refraction by spherical surfaces. The base, or blank, itself must first be polished to closer than l>10 for green light. Rotator 1u : u + b2 Rotator c cos b sin b - sin b d cos b As an important example, consider the production of circularly polarized light by combining a linear polarizer with a QWP. The phenomenon of beats provides a sensitive method of measuring the difference in frequencies of two signals of nearly the same frequency. The other, drawn as a double-headed arrow, lies in the plane of incidence, that is, the plane of the page, as in Figure 4b. Before focusing, a plane mirror is used to divert the converging rays to a secondary focal point, fs , near the body of the telescope, where an eyepiece is located to view the image. Its action on the incident linearly polarized light is to convert it to linearly polarized light perpendicular to the original direction, or at - 45° inclination with the x-axis. A small photocell is moved along the central axis, recording the power density of the diffracted beam. In Figure 11, we generalize Figure 3 by defining distances locating the six cardinal points relative to the input and output planes that define the limits of an optical system. (11) and (12), the irradiance is a maximum at u = 0 1y = 02 and drops to zero at values ym such that ym mlf b (13) The irradiance pattern is symmetrical about y = 0. Even the infrared radiation around 900 nm from a galliumarsenide semiconductor laser can be seen as a deep red. 3 Show that Eq. (16) follows from Eq. (15). The same is true for the off-axis point T and its image, T¿. Unpolarized light Air Water n 1.33 Glass block n 1.50 Figure 25 Problem 12. New York: Plenum Press, 1980. (See Figure 4.) 10 A signal of power 5 mW exists just inside the entrance of a fiber 100 m long. 14–16 San Francisco: W. 32. New York: John Wiley and Sons, 1983. Solid solutions of similar compound semiconductor materials produce output in a variety of spectral regions when the composition of the alloy is varied. Because of phase reversal, originally diverging rays—as those in EH2 , which form a virtual image—become converging and focus as a real image on the viewing side of the hologram. First, sources with a stable wavelength output at each of the wavelengths used in the different channels must be available. Fraunhofer Diffraction 289 (a) N 2 (b) N 3 (c) N 4 (d) N 5 Figure 17 Diffraction fringes produced in turn by two, three, four, and five slits. The light power incident at the image plane (irradiance Ee in watts per square meter) depends directly on (1) the area of the aperture and inversely on (2) the size of the image. If the two planes are not orthogonal, a rather rare condition called irregular astigmatism, the surface anomaly is not so easily corrected. 17 A 5-cm focal length camera lens with f/4 aperture is focused on an object 6 ft away. CO2 lasers are typically pumped by an electric discharge. The B vector sum E executes oscillations along the x-axis as the EP- and EC-vectors rotate clockwise and counterclockwise, respectively, at equal rates. Combining this result with our understanding of the equivalence of Fourier transform and spatial frequency spectrum (or Fraunhofer diffraction function) of an aperture function, we can read Eq. (33) as follows: The spatial frequency spectrum of image irradiance is equal to the product of the spatial frequency spectrum of object irradiance and the spatial frequency spectrum of the point spread function. Fraunhofer pattern that results from more complicated aperture functions by using the convolution theorem. Each modification improves the coherence of the light given off by the source, but at the expense of a drastic loss of light energy. Copyright © Springer-Verlag GmbH & Co KG. At what wavelength does a blackbody at 6000 K radiate the most per unit wavelength? over a 10-cm grating width, determine (a) the minimum number of grooves/cm required; (b) the optimum blaze angle for work in this region; (c) the angle of diffraction where irradiance is maximum (show both blaze angle and diffraction angle on a sketch); (d) the dispersion in nanometers per degree. Apparently then, the Gaussian beam is not brought necessarily to a focus in the focal plane of the lens, that is, at a distance f to the right of the lens. The Pump The pump is an external energy source that produces a population inversion in the laser gain medium. Take n = 1>1.5 to reproduce Figure 6 and then make similar plots for n = 1>1.3 and n = 1>2.42. Optics of Thin Films, an Optical Multilayer Theory. Thus the relation given in part (a) of Example 6, derived there for a Q-switched system, also applies for the mode-locked case. have supposed to be a minimum. The differential wave equation to be satisfied by the E-field is then §2E = a 1 0 2E s 0E b 2 + a 2b 2 0t c 0t e0c (53) Note that, compared with Eq. (51), the new wave equation, given as Eq. (53), includes an additional term involving the conductivity and the first time derivative of E. The population densities of the different energy states in the medium determine the amount of attenuation or amplification that a given electromagnetic field will undergo. Figure 24 illustrates the working principle of the simple magnifier. A three-dimensional view of the object from all sides can be produced on a holographic film that is wrapped around the object on a cylindrical form, as shown in Figure 4. Extrinsic losses of a geometric nature include sharp bends in the fiber as well as microbends, both of which cause radiation loss because the condition for total internal reflection is no longer satisfied (see Figure 5). Nonlaser light sources emit light primarily via the uncorrelated spontaneous emission action of many atoms. Suppose, however, that the model of the fish has undergone some small changes in shape, by thermal expansion, for example. Equation (7) describes the Cartesian ovoid of revolution shown in Figure 13a. (b) The first few zeroes and maxima of the normalized irradiance I>I0 = 12J11g2>g22. These angles are seen to be precisely complementary, as required by geometry and the definition of Brewster's angle. An Introduction to Coherent Optics and Holography, 2d ed. That stimulated emission produces a "twin" photon, which accounts for the unique degree of monochromaticity, directionality, and coherence associated with laser light. Any electromagnetic wave can be regarded as a superposition of plane electromagnetic waves with various frequencies, amplitudes, phases, and polarizations. With the active material in place, the optical activity is measured by the angle b required to reestablish extinction. (Courtesy of Burroughs Wellcome Co.) Parts of the Eye The basic parts of the eye are shown in Figure 1. Using this form for the phase difference between the two beams and using common trigonometric identities, the detected power can be written as P0 P0 P0 11 + cos d2 = 11 + cos1p + dg22 = 11 - cos1dg22 2 2 2 = P0 sin21dg>22 Pdet = For small arguments, the sine function can be approximated by its argument so that Pdet L P01dg>222 The phase difference induced by the gravitational wave is dg = k¢s, where ¢s is the difference in path lengths traveled by the beams passing through the two arms of the interferometer. The other component, however, propagates with a refractive index ne = n7 = c>y7 . This equality of the rate coefficients, and Eqs. Calculate the minimum (a) resolving power and (b) plate separation that will accomplish the resolution of the two components of the H-alpha doublet of the hydrogen spectrum, whose separation is 1.360 nm at 656.3 nm. Tolansky, Samuel. The film has been deposited on some substrate S. Because of the divergence of the rays entering the lens, however, the length of the focused line image AB is no longer equal to the effective length CL of the lens. Linear Polarization (w mp) ~ E General: 0 ~ Vertical: E0 ~ At 45: E0 cos a sin a ~ 0 1 1 0 Horizontal: E0 1 2 ~ 1 1 1 At 45: E0 2 1 1 45 45 II. What is the maximum frequency of input pulses that produce nonoverlapping pulses on output due to this case of modal dispersion? Using an average wavelength of 570 nm, what is the angular diameter of the star? Figure 8 illustrates spectral absorption in silica and plastic fibers. The message source might be audio, providing an analog electrical signal from a microphone; it might be visual, providing an analog signal from a video camera; or it might be digitally encoded information, like computer data in the form of a train of pulses. The calcium (Ca) atom is positioned at some distance above the carbon atom, at the apex of the pyramid. The root idea had been introduced by Hero of Alexandria, who lived in the second century B.C. According to Hero, when light is propagated between two points, it takes the shortest path. To form a faithful, detailed image of the external object, the eye relies on its visual acuity. For example, when a = 2b, then p = 2m = ; 2, ; 4, ; 6, Á gives the missing orders of interference. Compare your answers with the values given in the table. In this case, the intermediate image I must be located outside the ocular focal length fe . The various parameters are k32 = 108>s, k21 = 103>s sp = s31 = 3 # 10-19 cm2, s21 = 10-18 cm2 l31 = 400 nm, l21 = 600 nm NT = 1.5 # 1026>m3 1in free space2 a. All other field shapes see a high loss and so do not lase. Through lens L1: s1 = 3 cm, f1 = 6 cm so 13 + 1s1œ = 16 gives s1œ = -6 cm. To record sharp images under these conditions, the film must be shaped to fit the Petzval surface. L P S T 3 Optical Instrumentation INTRODUCTION The principles of geometrical optics are applied in this chapter in order to discuss several practical optical instruments. f (x) = (4/)(sin kx + 13 sin 3kx + 15 sin 5kx + ⋯) E E 2E f (t) = 0 + 20 cos t + 30 cos 2t 2 2 g() = h e(−)/2 √2 672 (a) 32 million (b) 0.67 million (b) 1284 (a) 68.1° (b) 0.567 (c) 34.5° (a) 0.64 (b) 79.5° (c) 6624, 3281 (c) 432 μm; 429 μm; 10.07 m 159 10.2 μm 12 and 120, counting both polarizations −70 db/km 0.080 mW 3.33 km; 10 km 0.136 db/km (b) −1.25 db, −6.02 db, −10 db, −20 db (a) 1.0069 km; 1 km (b) 4.900 μs; 4.867 μs 431 ns; 2.32 MHz 77.2 ns 14.6 ns/km 457 ps; 1/146 25 MHz (a) 4 ns (b) 0.4 ns 48.9 ns (b) 3.9 ps/km; 4.3 ps/km (a) 50.5 ns; 1.075 ns; 0.075 ns (b) 50.5 ns (a) 100 GHz (b) 4 THz (a) No ΔL satisfies Eqs. r¿ Employing the Huygens-Fresnel principle, as in Fraunhofer diffraction, we seek to find the resultant amplitude of the electric field at P due to a superposition of all the Huygens wavelets from the wavefront at the aperture, each emanating from an infinitesimal region on the wavefront of elemental area dA. In this situation the n-type side of the junction will be at a higher voltage than the p-type side of the junction. That is, the standing wave normal modes of the cavity have wavelengths such that an integer number of half-wavelengths "fit" into the cavity length. The focal points F1 and F2 are located at distances f1 and f2 from the principal points H1 and H2 and at distances p and q from the reference input and output planes, respectively. This wave phenomenon has its analogy in the reflection of waves from the fixed end of a rope. The geometrical extensions denoted by the dashed lines in Figure 4, identifying triangle ACA¿, make it evident that ¢ = AB + BC = A¿B + BC = 2n1d cos w (7) so that the possible modes are given by m = fr 2n1d cos w + p l Now, since fr ... p, the second term is 1 at most and is typically negligible compared with the first term. Irradiance fluctuations about the constant bias comprise the spectral distribution (interferogram) given by q I1x2 = L0 I1k2cos1kx2 dk (41) which is the (cosine) Fourier transform of the spectrogram, 2 I1k2 = a b I1x2cos1kx2 dx p L0 q (42) Thus, detection of the interferogram output I(x), as a function of path difference x, at a point on the optical axis of the system enables one to calculate the spectral irradiance distribution I(k) as a function of wavenumber by the Fourier-transform integration indicated in Eq. (42). To aid a discussion of this evolution, consider Figure 16. A network of such corner reflectors ensures the exact return of a beam of light—a headlight beam from highway reflectors, for example, or a laser beam from a mirror on the moon. (15) and (16) that L1 = L2 . Reproduce as completely as possible the line image of the point. The two dimensions are those of the page on which we have been drawing our ray diagrams. The coherence length of typical laser sources ranges from tens of centimeters to tens of kilometers. Formal proofs can be found in any standard textbook on matrices and determinants, for example, E. 8 A thin lens is used to image an object 1 m from the lens onto a CCD array 10 cm from the lens. It has the property that as u approaches 0, the function approaches a value of 1. Considering both TE and TM modes together, it follows that the reflected light is partially polarized with a predominance of the Es mode present. The redshift is the shift in wavelength of such radiation toward longer wavelengths, due to a relative speed of the source away from us. Recalling that the ray represents plane waves moving up and down in the waveguide, it is evident that such waves overlap and interfere with one another. This leads to the equation ml = 2lS sin u = 2lS sin £D 2 (16) a relation worked out in this context by Brillouin in 1921 and identical to the Bragg equation for X-ray diffraction.14 In Eq. (16), the angles and optical wavelength are those measured within the medium. This is not, however, a fundamental physical distinction. For an off-axis object at infinity, the zones are straight, parallel interference fringes. Since such a relationship cannot depend on the arbitrary choice of a boundary point Br nor a time t, it follows that the phases of the three waves, which depend on Br and t, must themselves be equal: 1k # Br - vt2 = 1kr # Br - vrt2 = 1kt # Br - vtt2 B B B (4) In particular, at the boundary point Br = 0 of Figure 1, - vt = - vrt = - vtt or v = vr = vt (5) so that all frequencies are equal. Another conclusion that is of some historic interest follows from a consideration of the effect at P when a round obstacle or disc just covering the first zone is substituted for the aperture. As another example, consider the superposition of vertically and horizontally linearly polarized light in phase: 0 1 1 c d + c d = c d 1 0 1 The result is linearly polarized light at an inclination of 45°. The visible spectrum of colors ranges from red (long-wavelength end) to violet (short-wavelength end) and is bounded by the invisible ultraviolet and infrared regions, as shown. For night viewing, when the pupils are somewhat larger, a rating of 7 * 50, producing an exit pupil diameter of 7 mm, would be preferable. We display this behavior by a double-headed arrow, as shown in Figure 2a. The small-signal gain coefficient, built while the cavity had a high loss rate, now exceeds the high-Q Q . In either case, nearly parallel rays of light from a distant object are collected by a positive objective lens, which forms a real image in its focal plane. Finally, computer ray-tracing methods for tracing a given ray of light through an optical system are briefly described. Show that the fringe visibility may be expressed by 12 Determine the linewidth in angstroms and hertz for laser light whose coherence length is 10 km. What is the maximum ratio of beam irradiances there? The half-angle beam divergence u = l>1pw02 is valid only in the far field. TABLE 1 RADIOMETRIC TERMS Term Radiant energy Radiant energy density Radiant flux, Radiant power Radiant exitance Irradiance Radiant intensity Radiance Symbol (units) Defining equation Qe1J = W # s2 we1J>m32 £ e1W2 Me1W>m22 Ee1W>m22 Ie1W>sr2 W Le a b sr # m2 we £e Me Ee Ie = = = = = — dQe>dV dQe>dt d£ e>dA d£ e>dA d£ e>dv Le = dIe>dA cos u Abbreviations: J, joule; W, watt; m, meter; sr, steradian. What is the permissible speed such that the object does not move more than l>10 during the exposure? To achieve some measure of coherence with a nonlaser source, two modifications to the emitted light can be made. (a) (b) (c) (d) wave.) More complex filtering has also been used in image restoration, for example, in the deblurring of lunar photographs. The linewidth of a single mode in the output of a laser is typically governed by environmental noise such as mechanical vibrations, which change the cavity length, or index of refraction variations in the gain medium. Two common uses of the Fabry-Perot as a control element are as a means of limiting a laser to single-mode operation and as a component in a laser frequency stabilization system. Of course, a complete specification of the full electric field vectors of plane waves and Gaussian beams also requires knowledge of the polarization of the fields. 4 An equiconvex lens having spherical surfaces of radius 10 cm, a central thickness of 2 cm, and a refractive index of 1.61 is situated between air and water 1n = 1.332. In contrast, as mentioned, a laser source, by the very nature of its production of light via stimulated emission, ensures both a narrow-band output and a high degree of phase correlation. 22 Based on the plots obtained in problem 21, describe how an adjustable aperture can be used in a laser cavity to ensure that only the TEM00 cavity mode would be present in the laser output. Since the molecule, and so also the crystal, is B symmetric with respect to this direction (from C to Ca), both E-vibrations interact with the electrons in the same way when traveling through the calcite. Thus ƒ b ƒ represents the magnitude of the phase difference, at point P, between waves from the center and either endpoint of the slit, where ƒ s ƒ = b>2. Emitting area m 0m 20 TABLE 1 LASER DIODE WAVELENGTHS Material Wavelength (nm) GaN AlGaInP GaAlAs InGaAsP Sb mixtures 400–480 630–690 750–900 1200–2000 2000–4000 579 Laser Operation PROBLEMS 1 The spectral energy density r1n2 in an electromagnetic field in thermal equilibrium at temperature T is given by Eq. (6). To find the fraction of incident power that passes through a circular aperture (lens, diaphragm, etc.) of radius a, we revisit the expression for the Gaussian-beam irradiance I given in Eq. (25). The generation of LIGO interferometers under construction in 2005 is predicted to be sensitive to gravitational strains of less than 10-21 , and the next generation of devices is predicted to have strain sensitivities of less than 10-22 , both for signals with frequencies in the range of 100–1000 Hz. To detect these tiny gravitational strains, environmental signals due to seismic activity and a variety of other sources must be either reduced in size or filtered. The double sums represent all the cross products, excluding—by the use of notation j 7 i—the self-products already accounted for in the first term and also avoiding a duplication of products already tallied by the factor 2. nR 1.0 0.10 0.10 0.01 0.01 1014 1015 1016 1017 Extinction coefficient nI Refractive index nR 1.0 1018 Frequency (rad/s) PROBLEMS 1 In general, the "electrical constant" K, the dielectric constant, is related to the refractive index by K = n2 a. Mirror Film Holography 4 HOLOGRAM PROPERTIES As stated earlier, the entire hologram receives light from each object point in the scene. As v increases toward v0 , the refractive index increases slightly, as shown in Figure 2. 6 Calculate the skin depth in copper for radiation of (a) 60 Hz and (b) 3 m. The incoming beam is highly collimated so that its wavefronts are very nearly planar. With a lens separation somewhat less than f, however, the requirement on L that corrects for transverse chromatic aberration is somewhat violated. The energy is emitted over a broad continuum of wavelengths. One way of forming a suitable wedge for experimentation is to use two clean, glass microscope slides, wedged apart at one end by a thin spacer, perhaps a hair, as in Figure 15b. Recall that in this case the population of the lower lasing level N1 is negligible since we take t1 L 0. 23 What is the angular half-width (from central maximum to first minimum) of a diffracted beam for a slit width of (a) l; (b) 5l; (c) 10l? The temporal coherence, also called "longitudinal spatial coherence," is many orders of magnitude above that of any ordinary light source. To see that these equations represent the sequence in Figure 5, we take their real parts and set E0x = E0y = A and e = p>2, giving t T/4 Ey ⩽A Ex 0 (b) Ex = A cos vt y Ey = A cos avt - A p b = A sin vt 2 x E 2 = E 2x + E 2y = A21cos2 vt + sin2 vt2 = A2 (8) To determine the normalized form of the vector, notice that 12 + ƒ i ƒ 2 = 1 + 1 = 2, so that each element must be divided by 22 to produce unity. Experiment to find the range of distances over which you can detect the separation of lines placed 1 mm. When the reflecting surface is that of a homogeneous dielectric—the case we have been discussing in this chapter—the conductivity s of the material is zero. Wolbarsht. Next, consider the first two members of Eq. (6), which govern the relationship between the incident and reflected waves. For example, lightbulbs spread their output uniformly in all directions so that the irradiance 1 m from a lightbulb with a light power output of 10 W would be I = P>A = 10 W P = 4pr2 4p11 m22 = 0.796 W>m2 Irradiance 1 m from a 10-W lightbulb The output from a He-Ne laser, on the other hand, is concentrated in the thin beam of light emerging from the laser. The interferometer is therefore of the amplitudesplitting type. 3 471 Fourier Optics Aperture function for an array of slits Aperture function for a single slit Aperture function for a grating Figure 9 Symbolic representation of the convolution theorem for a grating. The special advantages of this technique have K (b) Figure 10 (a) Irradiance sinusoids of object and image, both of spatial frequency K. For a ray incident from the second medium, we define similar quantities, which we distinguish with prime notation, r¿ and t¿. A calculation similar to that carried out in Example 3 reveals that in this case I1st min = 0.78Iu . (6), (7), (10), and (11) to make use of those members previously ignored in first finding the transfer matrix. Of course, prisms alone cannot produce images. If the incident light is white and l0 is in the visible region, the reflected light is colored. Integrated Gain Using Eq. (37) in Eq. (36) results in a differential equation that can be integrated to provide a relation between the irradiance I0 input into a gain medium and the irradiance IL output from that gain medium. How does the polarization of the emergent light vary as a function of u? In this approximation, where we allow only such paraxial rays2 to form the image, the angles of incidence and refraction are both small, and the approximation sin u tan u u 1in radians2 is valid. By what percentage difference does the ratio of the film indices differ from the ideal? If such a resonance occurs in the visible range of frequencies, for example, the material absorbs a portion of the spectrum and appears colored, while transmitting the remainder. Below 100 nm, gold and platinum are often used. Equations (3) to (5) then take the simpler forms for photons: p = E c (6) l = h hc = p E (7) y = pc2 = c E (8) Thus, while nonzero rest-mass particles like electrons have a limiting speed of c, Eq. (8) shows that zero rest-mass particles like photons must travel with the constant speed c. 13 Carry out the integration necessary to verify the claim that the total power carried in a TEM00 beam is £ tot = I0 pw20 2 14 Carry out the integrations necessary to show that the fraction of the power in a TEM00 beam that is transmitted through a 2 2 circular aperture of radius a is 1 - e-2a >w . 4 REFLECTION IN PLANE MIRRORS Before discussing the formation of images in a general way, we discuss the simplest—and experientially, the most accessible—case of images formed by plane mirrors. A pinhole does no focusing and actually blocks out most of the rays from each object point. Each view is complete, exhibiting both depth and parallax.

principal maximum of order m, we have by the grating equation (2), a sin um = m1l + dl2 (9) 297 The Diffraction Grating To satisfy Rayleigh's criterion, this peak must coincide (same u) with the first minimum of the neighboring wavelength's peak in the same order, or a sin um = a m + 1 bl N (10) Equating the right members of Eqs. Solution lm fsr = ll m 295 The Diffraction Grating Thus, l1fsr = 400 = 400 nm 1from 400 to 800 nm in first order2 1 l2fsr = 400 = 200 nm 1from 400 to 600 nm in second order2 2 l3fsr = 400 = 133 nm 1from 400 to 533 nm in third order2 3 13 DISPERSION OF A GRATING Higher diffraction orders grow less intense as they fall more and more under the constraining diffraction envelope. 31 Show that the minimum distance between an object and its image, formed by a thin lens, is 4f. Using this in Eq. (32) gives RM1 = - d11 + z20>d22. The corrective contact lens should produce an image of an object at infinity. The corrective lens should form an image of an object at infinity (s = q 2, for which the corrective lens are to add to a pulse, they must be locked to a common phase at a particular place that moves back and forth through the cavity at the speed of light. (a) 1.88 × (b) 6330 × 2. Indium gallium arsenide phosphide (InGaAsP) laser diodes can be engineered to emit near 1550 nm. Short-wavelength waves, corresponding to surface ripples, have a velocity given approximately by yp = a 2pT 1>2 b lr where r is the density and T is the surface tension. So the image is virtual, 12 cm to the right of L1 , of half-size given by (3 cm) * A -ss¿ B = 13 cm2 A - -412 B = 9 cm. In this section we discuss three such procedures; radial keratotomy, corneal sculpting, and conductive keratoplasty. We are looking for the irradiance at a point like P¿ in Figure 15a. Victories for the wave theory continued up to the twentieth century. As discussed in Section 2, the maximum wavelength separation that can be resolved is the free spectral range of the device, so that clmax = ffsr . V. Ch. 50. The latter property describes the resolution of the recorded spectrum. This is the content of Babinet's principle, which we express as EA + EB = Eu Figure 18 Fresnel shadow of a screw. Gravity waves propagating in other directions will also cause differing length changes in the two arms. In the case of ordinary lights, smaller than those now attainable with high-energy lasers, the net fields are assumed to be a linear superposition of the constituent fields. 16 Consider a myopic, presbyopic eye with a near point of 13 cm and a far point of 15 cm. We conclude from Eq. (59) that the wave propagates in the material at a wave speed c>nR and is absorbed such that the amplitude decreases at a rate governed by the - exponential factor e -1vnIs>c2. Thierer, Atlas of Optical Phenomena, Plate 9, Berlin: Springer-Verlag, 1962.) r2m = 2Rtm = 2R a ml b = mRl 2 r21 = 11214.18421589.3 * 10-92 m2 = 2.466 * 10-6 m2 r210 = 110214.18421589.3 * 10-92 m2 = 24.66 * 10-6 m2 or r1 = 1.57 mm and r10 = 4.97 mm. Over a small enough region (or sufficiently far from the source), the spherical wavefronts associated with a spherical wave are approximately planar. In this case, the resultant wave can be formed as ER = E1 + E2 = E01 cos1a1 - vt2 + E02 cos1a1 + 2mp - vt2 = 1E01 + E022 cos1a1 - vt2 Destructive Interference If two harmonic waves of the same frequency are "out of step" in the sense that the peaks of one always coincide with the troughs of the other, the waves are said to destructively interfere. A bit of analysis (see problem 17) indicates that decreasing the cavity losses not associated with the laser output also increases the laser output irradiance. 22 Chapter 2 Geometrical Optics x is then given by the preceding condition, since ui = ut and 2 c · x 2a + x2 sin ut = - giving 2b2 + 1c - x22 sin ut sin ut = 0 yt yt Simplifying the equation and proceeding to zero, we obtain at once yt sin ui = yi sin ut . How many well-defined beams are broadcast and what are their angular half-widths? 4 Looking into a Michelson interferometer, one sees a dark central disk surrounded by concentric bright and dark rings. If the radius of 65.2 cm on the object side of the lens and 545 cm on the image side. Further, it is difficult to limit a diode laser to stable single-mode output, and so diode devices generally have shorter coherent lengths than, for example, do Nd:YAG, He-Ne, or Ar+ laser devices. Boston: Academic Press, 1988. This analysis for the slab waveguide has served to elucidate the physical reasons for mode restriction. The family of spherical surfaces normal to the rays are the wavefronts, the locus of Real object space O Real image space Optical system I Figure 10 system. Here the solid angle dv = dA>r2. McDonald, Am. J. However, even very low level environmental noise processes lead to power signals of this and greater levels. re 401 Matrix Methods in Paraxial Optics Incorporating the paraxial form of Snell's law, nu = n¿u¿ we have a¿ = a y y y n n bu = a b aa + b n¿ R n¿ R R a¿ = a n n 1 ba - 1by + a ba R n¿ n¿ or The appropriate linear equations are then y¿ = 112y + 102a a¿ = a n n 1 ba - 1b dy + a ba R n¿ n¿ or, in matrix form, y¿ C 1 S = C 1 a n - 1b a¿ R n¿ Here, we use a sign convention for R that should be familiar to you. Newton's second law, applied to the electron in the model of Figure 1b, then leads to the equation of motion, - KSBr - mg drB d2Br B - eE = m 2 dt dt (3) In Eq. (3), KS is the spring constant, m is the electronic mass, and g is a frictional constant with dimensions of reciprocal time. 151 152 Chapter 6 Properties of Lasers Mirror 1 Gain medium (a) Mirror 2 Pump (b) Output Figure 16 Time development of the startup of laser oscillation in a typical laser cavity. The pump creates a population inversion in the gain medium. We conclude P = a B F B bE 1 - F>3e0 (9) By the multiplier of E in Ne2>3me02 - v2 - ivg Let us define v20 as the quantity in parentheses, that is, v20 K KS Ne2 m 3me0 (10) Then, Eq. (9) becomes B P = Ne2>m v20 - v2 - ivg B E (11) Forming the magnitudes of both sides of this relation shows that the magnitude of the polarization is related to the magnitude of the applied field by the relation ƒ Pƒ = ƒ 21v20 Ne2>m B v2 + vg 2 2 2 2 ƒEƒ Clearly, ƒ P ƒ can increase dramatically as v : v0 , so that v0 represents a resonance frequency for the dipoles of the medium. fe 80 Chapter 3 Optical Instrumentation Substituting Eq. (41) into Eq. (40), M = 25ffe = fe d1 - fe2 Based on an algebraic manipulation of the thin-lens equation, however, we can show that the ratio of image to object distance, soœ >so , for the objective lens is d - fe - fo soœ = so fo (43) where we have used the fact that soœ = d - fe , evident in the diagram. Determine the waveguide dispersion in ps/km at l = 1.27 and 1.55 mm for a source with a spectral width of 1 nm. These values occur whenever sin kx = 0, or kx = 2px = mp, 1 m = 0, ; 1, ; 2, A or l l3Ix = m a b = 0, , l, , Á 2 2 2 (24) Such points are called the nodes of the standing wave and are separated by half a wavelength. The change to negative coordinates is required by the inversion of the image relative to the object. 8.11 By taking appropriate expressions for k # Br , write equations describing a sinusoidal plane wave in three dimensions, displaying wavelength and velocity, if propagation is a. Applications of OPC include aberration correction and pointing and tracking. Also, first and second focal lengths are equal in magnitude, and the usual thin lens equations, 1 1 1 + = so si f and m = - si so (6) are valid. Show that the phase delay of the diverging subject beam, at a point on the film a distance y from the axis, is given by py2>ld, where d is the distance of the point source from the film. V = 2 2I1I2 ƒ g1t2 ƒ 1I1 + I22 b. Independent point sources S1 , S2 , and S3 are shown, all contributing to the intensity of the light at P. If the surface is instead concave, R is negative. Find and plot the steady-state small-signal population inversion N2 - N1 as a function of the pump irradiance. The mass of each hydrogen atom is about 1.67 * 10-27 kg. The first laser, developed by T. Lens Sun dL 5 cm Image u fL 50 cm Figure 38 Problem 18. This mode is called left-circularly polarized (LCP) light. (9) and (10), we obtain l>dl = mN. Rotation of the polarizer now can produce zero intensity. François, M. Each curve corresponds to a different film index, but the glass substrate index has been chosen ns = 1.52 in all cases. In this case, all other coefficients vanish. We turn now to an important use of a multiple-beam instrument, the Fabry-Perot interferometer. Through which output port would light of wavelength l1 = 1548 nm exit? Its size, based on O¿P¿, is (- 1.5 cm) A - -105 B = - 3 cm. (b) Rochon prism. The result is a filter with a pass-band width of perhaps 15 Å and 40% transmittance. Equation (4) or (7) indicates that, as d is varied, a full cycle in the emission in the derivation of this rate equation. Since a phase difference is given in general by k¢, Eq. (7) indicates a path difference associated with b of ¢ = 1b>22 sin u, shown in Figure 1 the correct aberrations, in supermarket scanners, and in heads-up displays for aircraft pilots. 25. Nonlinear optics is a burgeoning field driven by the availability of high-power/short-pulse electromagnetic radiation. Fraunhofer Diffraction umin u Figure 10 Rayleigh's criterion for just-resolvable diffraction patterns. Rays reflected from the top and bottom plane surfaces of the film are brought together by the lens. dimensional diffraction pattern. When squared, the reflectance as a function of wavelength is determined. Photometry and Radiometry for Engineers. The objective lens, being larger in diameter than the pupil of the eye, permits the collection of more light and makes visible those point sources such as stars that might otherwise not be detected. The general description of the instrument reflects the wide variety of designs and uses of interferometers. The direction of the electric field vector E is known as the polarization of the electromagnetic wave. Unlike the Fresnel circular zones, the areas of the Fresnel strip zones fall off markedly with n so that successive phasor amplitudes of the zonal contributions are distinctly shorter. After a moderate amount of algebra, one finds r1 = n2 - n1 e2 - Ad(0 ad01 - Ad2 r2 - Ads0 (30) (31) 173 Optical Instrumentation where the quantity a = rL - 1 n. Finally, in a Q-switched system, the cavity is switched to the high-loss state after the pulse has driven the population inversion below threshold and before the inversion can begin to grow again. The light waves interact with one another and with the medium. The real or apparent point of intersection is interpreted as the emanation point of these rays. 20 Calculate the delay due to modal dispersion in a 1-km GRIN fiber with ap = 2. Parallel rays form a line image that is parallel to the cylinder axis. The array of blade edges effectively traps the incident light, resulting in almost perfect absorption. Benjamin, 1964. The frequency shift due to a moving observer is based physically on the change in speed of the sound waves relative to the observer. possess a frequency-dependent phase relative to If we were to associate B the symbol E with the externally applied field, our analysis, thus far, would B apply only to the case of a single dipole oscillator. 2) is awkward to refer to the energy levels of atoms or molecules or liquids or solids, so, at this point, we begin to refer to the energy levels of atoms with the understanding that the discussion at hand may also be applicable to other quantum systems. 8 A lens has the following specifications: R1 = 1.5 cm = R2, d(thickness)2 = 2.0 cm, n1 = 100, n2 = 1.63, n3 = 1.30. 17 Determine the length and base area of the cylindrical volume within which light received from the sun is coherent. In a color plasma display, gas cells are grouped into sets of three subpixels. What is the beat frequency between the incident and reflected light? The temporal coherence is perfect S two, for example, M. One meter from the output end of a He-Ne laser the beam radius might be about 2 mm. 1 FOURIER ANALYSIS When a number of harmonic waves of the same frequency are added together, even though they differ in amplitude and phase, the result is again a harmonic wave of the given frequency. 16 In this problem and the following two problems, consider a ring cavity like the one depicted in Figure 8. (36) and (37). We have indicated that EM waves may lose and gain energy only in discrete amounts that are multiples of the energy associated with the energy quanta that have come to be called photons. New York: Academic Press, 1974. In Table 2, representative values of these figures of merit, as well as some other quantities, are listed for 8 different mirror reflection coefficients. (c) Ellipsoid surface images point O at infinity when O is at one focus and n2 > n1. The linear susceptibility for KDP can be found from the relation given earlier, n = e0x1 e c = = 1x1 y e0 A e0 Therefore, x1 = n2 = 1.52 = 2.25. In a Q-switched system, the population inversion grows to a value larger than the low-Q, high-loss cavity prevents the growth of the cavity field until the population inversion grows to the maximum value allowed by the pump/spontaneous-decay-rate dynamics. A maximum in the interference pattern occurs at P if P lies on the perpendicular bisector of the two slits. If light represented by Jones vector V passes sequentially through a series of polarizers represented by M1 , M2 , M3 , A , Mm , so that V¿ = MmA M3M2M1 * V. Ray 2: As indicated in Figure 8, we will take the steady-state irradiance at the input end of the gain cell to be 20 and that at the output end to be IL . When using monochromatic light, the net shift of fringe systems is ambiguous because a shift ¢x = 0.5x, for example, will look exactly like a shift ¢x = 1.5x. In all cases, nH = 2.35, nL = 1.38, ns = 1.52, and n0 = 1.00. Find the (a) window width xw ; (b) minimum resolvable wavelength interval at 400 nm; (c) minimum wavelength that is not subject to aliasing; (d) minimum sampling rate according to the Nyquist criterion. Discontinuities in the line segments occur each time the light is reflected or refracted. The Fresnel zones to which we shall refer are long, thin, rectangular regions as pictured earlier in Figure 9, rather than annular rings, as pictured in Figure 7. The lateral ray aberration by due to the ray from the neighborhood of P may then be approximated by by = au¿ = s¿da n¿ d(y) where s¿ is the paraxial image distance from the second lens and a has been taken from Eq. (1). When O is to the right, corresponding to a virtual object, is negative. (a) Solution In this case, t = r = l>2, so that Eq. (38) leads to an air-film thickness at the nth dark ring given by tn = ml>2nf . From the direction of the refracted beam (which may be calculated using B Snell's law), we conclude that the E-field within the isotropic dielectric material, and thus the axis of the dipole oscillations, is oriented perpendicular to the beam direction, as indicated by the double-headed arrows. Why is an ideal single lens necessary? The Porro prism, Figure 18d, consists of two right-angle prisms, oriented in such a way that the face of one prism is partially revealed to receive the incident light and the face of the second prism is partially to receive the reflected light. Still other practical solutions for double-layer antireflecting films become possible if the thicknesses of the layers are allowed to have values other than multiples of l>4. The individual matrices operate on the light ray in the same order in which the corresponding optical actions influence the light ray as it traverses the system. Birefringence indicates the possession of two refractive indices, whereas double refraction refers to the splitting of a ray of light into ordinary and extraordinary parts. Here we show, by using a Fourier series, the output plane thus functions as the second focal plane. Thus the irradiance at the center of the shadow of the obstacle should be almost the same as with no disc present! When Fresnel's paper on diffraction was presented to the French Academy, Poisson argued that this prediction was patently absurd and so undermined its theoretical basis. If an electromagnetic field consists of the superposition of fields with many different polarizations of which one is (or several are) predominant the field is said to be partially polarized. The greater its coherence time, the more monochromatic the source. In optical fibers this frequency shift is typically too small to couple the different channels in a WDM fiber. For Snelius, the normal eye could just resolve a letter that subtended 5¿ of arc at 20 ft, with 1¿ of arc contained in the details of the letter. (a) Newtonian telescope. London: Micrograms Publications Ltd., 1977. 5 Calculate the rectangular slit width that will produce a central maximum in its far-field diffraction pattern having an angular breadth of 30°, 45°, 90°, and 180°. In an ideal optical system, every ray from O intercepted by the system—and only these rays—also passes through I. Two important methods used to control the characteristics of laser light pulses are Q-switching and mode-locking. Locating the intermediate and final image. The nature of extraterrestrial solar radiation indicates that the sun behaves approximately as a blackbody with a temperature of about 6000 K at its center and 5000 K at its edge. The effect of placing the aperture stop on the image side of the lens can also be seen from the same figure by reversing all rays and the roles played by object and image. If the light in the cavity is sustained by an input as in a Fabry-Perot cavity, or by a pumped gain medium as in the case of a laser, tp is the approximate time that a given portion of the light field spends in the cavity. (46) and (47) for the case in which the lens is placed at the waist of the incident beam. Any arbitrary beam can be expanded as a linear combination of HermiteGaussian beams, each of which has the same propagation law, a = q0 + z. 25 Thus, the line image is parallel to the cylindrical axis, enlarged to 25 cm, and located 1 m from the lens. A 13 Line image B C 5 L 1 2 O 4 (plane) surface at exit, we obtain Parallel to cylinder axis 1.0 1.0 = - 0, which gives s¿ = 100 cm. 22 Determine the numerical aperture of a 1-m-length of fused silica fiber when the light source is (a) a LED centered at 820 nm with a spectral width of 40 nm and (b) a LD centered at 820 nm with a spectral width of 4 nm. The spectrum of spontaneous emission has the same frequency dependence as the lineshape function g1n2. The coherence length is the length along a wave train over which the phase of the wave remains correlated. The program should allow for the special cases of rays from far-distant objects and for plane surfaces of refraction. 25 A Newton's ring apparatus is illuminated by light with two wavelength components. The spectral radiation from a heated tungsten wire, for example, is close to that of a graybody with e = 0.4 - 0.5. Blackbody radiation is used to establish a color scale in terms of absolute temperature alone. Express this energy in J and in eV. Use a conservation of energy argument to show that the time-averaged energy density Ru9 associated with this field is related to the irradiance I of the field by Ru9 = I>c. Consider briefly the distinctive characteristics of this system. The points are then related as object and image points, as shown in Figure 9c, and the ray diagram is simply Figure 9b with all rays reversed. Elementary distortion of the wavefront when a plane wavefront enters the wave region. Note that these equations, which ensure a transmitted light with normal incidence, fail in such cases. (c) and image plane (a) Optical elements Optical system (b) Output plane (d) Figure 8 Diagrams illustrating the significance of the vanishing of specific matrix elements. Another situation in which the Doppler effect is of pivotal importance is the Doppler broadening of the spectral lines associated with the light emitted by the fast-moving atoms of a gas. Many optical applications depend critically on the nature and manipulation of the polarization of electromagnetic waves. The corresponding ranges of external angles of incidence at the first surface are 0° to 90° (TE mode) and 0° to up (TM mode). Recall that circularly polarized light consists of equal amplitude components with phases that differ by ; p>2. Calculate the irradiance at the surface. 5 A hollow glass sphere of radius 10 cm is filled with water. 474 Chapter 21 Fourier Optics yielding a receiving power of P K c 1 - dI1 (44) One sees that the resolution is improved by using large sample widths. (c) 2 In general, a paraxial ray is one that remains near the central axis of the image-forming optical system, thus making small angles with the optical axis. Research-quality gratings are usually of the reflection type. 553 Laser Operation Here n¿ is the center frequency of the spectral energy density of the electromagnetic field. This beam reconstructs the subject beam of Eq. (4) but with phase reversal, that is, with eu replaced by e -iu. What is the absorption coefficient of seawater for red light of this wavelength? In this way the pulse builds from phase-matched spontaneous emission events. This technique of pattern recognition is applied, for example, to the recognition and counting of small particles with different shapes, as in the case of blood cells, or to the search for characteristic patterns in aerial photographs, medical X-rays, and fingerprint files. The normalized irradiance function I>I0 (dashed line) for single-slit Fraunhofer diffraction is the square of sinc1b2. Nussbaum, Allen. Thus, this wavelength, like l2 = 1552 nm, would predominately exit Output 2. The sun subtends an angle of 0.5° at the earth's surface, where the illuminance is about 105 lx at normal incidence. A blackbody is an ideal absorber: All radiation falling on a blackbody, irrespective of wavelength or angle of incidence, is completely absorbed. (When describing theoretical resolution, it must be remembered that the Rayleigh criterion is somewhat arbitrary and that the spectral line widths also enter into the actual resolution.) A grating with 10,000 grooves/cm and 20 cm with provides a resolving power of 1 million in fifth order. In the latter application, instrument readings are projected so that they seem to be floating in space, allowing the pilot to retain a clear "heads-up" view of the scene in front of the aircraft. In either case, the light is refracted by the eyepiece in order to produce parallel, or nearly parallel, light rays. Chromatic aberration is eliminated by making use of multiple refracting elements of opposite power. Thus, to determine whether a given function of x and t represents a traveling wave, it is sufficient to show either that it is of the general form of Eq. (1) or that it satisfies Eq. (2). Of course, such a system does not really simulate the electronic frequency of the Fabry-Perot. When unpolarized light is input into such a filter, the output light will be linearly polarized along the low-loss direction, and the fiber functions as a linear polarizer. Take the transmission coefficients of the beam split- ters to be real. Light that is more monochromatic suffers less distortion due to material dispersion. The grooves ruled on a concave grating are equally spaced relative to a plane projection of the surface, not relative to the concave surface itself. n=1 Due to the action of the prism as a whole is the sum of the angular deviations at (2) at the first and second surfaces. Thus, if each beam-halving element that passes the laser beam in a given optical system has a diameter D equal to 3 times the beam spot size 1D = 3w2, nearly 99% of the beam gets through. 10, 11. First, consider a transparent, distorting medium like frosted glass, which is placed in the path of a light wave on its way to a PCM. Also find the minimum length d of an etalon that could be used to limit this laser to single-mode operation. Quite reasonably, fine features in the given f(t), such as the corners of the square waves, require waves of smaller wavelength, or higher frequency components, to represent them. When y V c, Eq. (44) is approximated by y l¿ = 1 - (45) 2 Robert Resnick, Basic Concepts in Relativity and Early Quantum Mechanics (New York: John Wiley and Sons, 1972), Ch. 2. It is helpful to break the distances AB and BC into parts and rearrange terms, resulting in ¢ = ml1AE + FC2 - n0AD) + nf1EB + BF2 (29) The quantity in square brackets vanishes, as we now show. Modern Optical Engineering. Refraction due to the thin glass window is negligible for the purposes here. Screen 20 Two microscope slides are placed together but held apart at one end by a thin piece of tin foil. A numerical aperture of 0.2 for example, corresponds to an acceptance cone of 74°. In optometric notation, the horizontal axis is referred to as the 180° axis, or simply "* 180," and the vertical axis as " * 90." Figure 7 indicates the optical conditions associated with the corrective prescriptions just cited for both myopic and hyperopic astigmatism. This quantity, often confused with irradiance, is given by le = dE dv (10) Differential solid angle dv measured in steradians (sr) is defined in Figure 2. For the identical optical system, the ray is in the reverse direction. Abramović et al., Phys. Let the axial progress of the ray be L, as shown, such that at point 1, the elevation and direction of the ray are given by "coordinates" y1 and a1 , respectively. If crosshairs or a reticle with a scale is used with the eyepiece to make possible quantitative measurements, then to be in focus with the image formed by the ocular EL, the crosshairs must be placed in the focal plane of EL conveniently attached to the field or aperture stop placed there (Figure 27). With the reference beam also present, however, the resultant 37? Holography amplitude EF at each point of the film—subject to the scalar approximation —is given by ER + ER + ES so that the scaled irradiance on the film is, IF = ƒ EF ƒ 2 = ƒ ES E...R + ES ...S + ES E...R + ER E...S + ER ...R + ER E...S ... E...S ... ...S ... E...S (6) The two terms now incorporate the important function x1, y2. Notice that if longitudinal chromatic aberration were absent, the transverse chromatic aberration could be interpreted as a difference in magnification of different colors. A lens of focal length 40 cm is used in a configuration like that shown in Figure 2. G (a) 3 SPHERICAL ABERRATION 1 IM fE f (b) Figure 6 Spherical aberration of a lens, producing (a) different image distances and in (b) different focal lengths, depending on the lens aperture. In this graph, the component of the electric field 109 Wave Equations y t0 p A y y z Ez (y t) ... E0 (sin1kz p vt1x y (a) Figure 12 Electric field polarization. Thus, the saturable-absorber Q-switch requires no Laser Operation 573 external intervention and the cavity is naturally Q-switched when the saturable absorber becomes transparent. In this case, the large number of photons in the cavity is due to spontaneous emission reaches a value large enough to saturate the absorber. A = 0.93933; B = 22.2212; C = -0.009284; D = 0.8448; r = r = 16.72 mm; s = w = -6.53 mm; p = -90.79 mm; q = 101.18 mm; f = -107.71 mm; the film plane is a distance q = 101.2 mm behind the last lens surface. The lens is used in air and has an axial thickness of 3 cm. 312 Chapter 13 Fresnel Diffraction and similarly, for the diffracted wave curvature in Figure 2a, z h2 71 2q (10) Combining Eqs. 22-24. 15 y0 y0 2 6 3 4 5 a0 y1 y1 y2 x0" x0 x1 x2 Matrix Methods in Paraxial Optics INTRODUCTION This chapter deals with methods of analyzing optical systems when they become complex, involving a number of refracting and/or reflecting elements in trainlike fashion. Stimulated Emission As shown in Figure 1b, when a photon of energy hn1,2 . E2 - E1 = hn0 encounters an atom initially in an excited state E2, the presence of the photon can stimulate or induce the atom to drop to the lower state, E1 . The ad hoc assumptions by Fresnel were shown by Kirchhoff to follow naturally by arising from Green's integral theorem, whose functions are scalar function solutions to the electromagnetic wave equation. 1 The corrected integral is the Fresnel-Kirchhoff diffraction formula, given by EP = - ikES ... cos ... (52) The approximation of the function e ikr, where f ... is the ... phase shift, and the obliquity factor F1u2 = 1 + cos u 2 limits the amplitude, ES . This is suggested by the schematic diagram of Figure 8 Operation of a linear polarizer. What is the visibility of the fringes when one mirror is moved 1 cm from the position of zero path difference between arms? We have If = 12 e0cE20l = 12 e0c1200022 = 5309 W>m2 I2 = 12 e0cE202 = 12 e0c1400022 = 21,180 W>m2 I12 = 2 2I1I2 cos e = 2215309 * 331802 = 25,640 W>m2 To find the visibility near this point of recombination, we must calculate Imax = I1 + I2 + 2211I2 = 5309 + 33180 + 2215309 * 331802 = 65,034 W>m2 Imin = I1 + I2 - 2211I2 = 5309 + 33180 - 2215309 * 331802 = 11,945 W>m2 The visibility is then given by Eq. (17) or visibility = 65,034 - 11,945 = 0.690 65,034 + 11,945 If the amplitudes of the two waves were equal, then Imin = 0, and the visibility would be 1. What frequencies appear in the polarization wave? Wavelets emerging from each slit arrive in phase at angular deviation of the first order from the axis of every path difference AB? 1N + a sin ul equals an integer number m of wavelengths. One sees that the Fabry-Perot could not differentiate between two signals which have very different wavelengths. The Nd:YAG laser is now commonly mode-locked. Solution Using Eq. (37), 6 10.22 1546 * 10-92 rl = = 1.1 mm ls 1 m * 10-4 Now suppose that the source slit in the example is made exactly 1.1 mm in width and that the separation between slits S1 and S2 is adjustable. Finally, the important differences between internal and external reflection are clarified. According to Snellen, the letters on the eye chart are constructed so that the overall block size of a letter, from top to bottom, or side to side, subtends an angle of 5¿ at the test distance. The portion of the wavefront that must pass through the thicker region is delayed relative to the other portions. Reynolds, George O., John B. This situation is typical of interference and diffraction phenomena: If the power density falls below the average at some points, it rises above the average at other points in such a way that the total pattern satisfies the principle of energy conservation. In 301 The Diffraction Grating (b) lens equation, Eq. (15), given the magnification of the microscope. By contrast, the quantum efficiency of photographic film is about 1%. E0 1 mm 45¿ Laser beam 1 1.14 Film Figure 30 Problem 27. Pulse broadening becomes zero at l = 1.27 mm and is negative as wavelength increases further. Leith and Upatnieks introduced an off-axis technique, using one or more mirrors to bring in the reference beam from a different angle so that the directions of the reconstructed real and virtual wavefronts are separated. Of course, the dimensions of the diffraction pattern also depend on the wavelength, as indicated in Eq. (14). Let us be a bit more specific. As shown, the arrows are drawn to indicate the direction in which the refractive index is relatively adjusted 45° counterclockwise by the Faraday rotator and in this orientation is fully transmitted by the analyzer. The objective lens is the lens nearer the object. The nature of the transmission in the polarization and reflected beams results of (b), calculate the image distance and lateral magnification for an object 20 cm to the left of the lens. M. Compared with modal distortion and material dispersion, waveguide dispersion is a small effect that becomes important only when the other pulse-broadening effects have been essentially eliminated. The quantitative treatment that allows us to make such calculations follows. As another example, consider a multilayer stack of alternating high-low index dielectric films (Figure 11). For other values of applied voltage, the light transmitted by the analyzer is elliptically polarized and is only partially transmitted. Of course, the subject is now absent. Alternatively, the Rs mode is called the TE (transverse electric) mode, and the Ep mode is called the TM (transverse magnetic) 8 mode, since the B-component of the wave is transverse to the plane of incidence B when the corresponding E-component is parallel to the plane of incidence. Determine the dispersive power of the prism. A simple example of such a field stop is the opening directly in front of the film that outlines the final image in a camera. Explain. In Example 3 we consider one such dependence. 83 On b 2 Set 4 Wave Equations INTRODUCTION In this chapter we develop mathematical expressions for wave motion in general but concentrate on the most useful special case, the harmonic wave. The total number of propagating modes m is the value of m when cos wm has its maximum value. This is sensible since for normal incidence there is no distinction between the two cases.1 In practice, measured reflection and transmission coefficients also depend on scattering losses from a nonplanar surface. Higher-order 1m 7 12 spots represent higher harmonics given by mnY1 . If the path length difference is as found from part (a), through which output port would light of wavelength l3 = 1555.6 nm exit the interferometer? When two transmission functions are put together, by physically placing two transparencies back-to-back in the aperture plane, how must the combined transmission function relate to the individual transmission functions? The uncoated surfaces of the slab have a reflectance 1r22 of 0.90. Each component produces an interference term with 1 7 E2 B B (E1 parallel to E2). At what depth is 99% of normally incident sodium light absorbed in tin? Knittl, Z. In the area of nonlinear optics, however, the controlled scattering of light from active media, exemplified by stimulated Raman, Rayleigh, and Brillouin scattering, provides much valuable information on the interaction of light and matter. The arrangement of prisms in Figure 16a, combined so that one prism cancels the dispersion of the other, can also be reversed so that the dispersion is additive, providing a prism spectrometer. Find the approximate group velocity in a glass whose dispersion curve is l>30 and for which n0 = 1.50. With this new relationship it is easy to show that ellipse Figure 4 Forms of harmonic waves: sin x = AcosA(kx - vt) (Figure 11). Since the angles a = 2pa α (8) sin x x (x). Thus, the argument of the sine or cosine, which depends on space and time, is called the phase, w. b) Zi (ti nn j) 13. We seek a relationship between s and s¿ that depends only on the radius of curvature R of the mirror. 1 DIFFRACTION FROM A SINGLE SLIT We first calculate the Fraunhofer diffraction pattern from a single slit, a rectangular aperture characterized by a length much larger than its width. Let us compare the peak power in a mode-locked, multimode laser to the average power in the same multimode laser system with CW output. Sources we call "monochromatic" emit light that can be represented as a sequence of harmonic wave trains of finite length, as suggested in Figure 7, each separated from the others by a discontinuous change in phase. In other applications, apertures may be introduced to produce a sharp border to the image, like the sharp outline we see looking into the eyepiece of an optical instrument. Of course, the real fields are given "by ER by B* = Re 1E"2 and EP = Re 1EP2. For the case at hand, the gain contribution is found by noting that each stimulated emission event increases the population of level 2 by 1 and increases the number of photons in the cavity by 1. The Wadsworth spectrograph Figure 12 uses a concave mirror, a concave grating, and a plate holder. Eq. (3) A = ALIs + ALIs = 1 = 3 if E = ƒ 622 = Guenther, Robert D. There is no reason that the state of polarization given by the two wave components, with amplitudes given by the Eq.(15), are realizable with full polarization. 18 Consider again the ring laser described in problem 16. Next suppose that the phase difference between orthogonal vibrations ' E0x and E0y is still p>2, but E0x Z E0y . If the spontaneous emission grows to a value large enough to saturate the absorber, the cavity will suddenly become low loss. The assumption is made to allow discussion of the fringe pattern in the correct and common situation. In any case, apertures are inevitably present because every lens or mirror has a finite diameter that effectively introduces an aperture into the system. The solid curve represents the population inversion Nlas as a function of time. Perhaps the oldest source of this kind is the carbon arc, still widely used in searchlights and motion picture projectors. 3 BANDWIDTH AND DATA RATE The more complicated the signal to be communicated, the greater is the range of frequencies required to represent it. Starting with the maximum aperture setting, supply the next three f-numbers that would allow the irradiance to be reduced to 13 the preceding at each successive stop. 178 Chapter 7 Interference of Light D u) ui nd O A C ut ut F E ut t ut Figure 12 Single-film interference with light incident at arbitrary angle ui . The free spectral range and FWHM of the transmittance T through a variable-input-frequency FabryPerot interferometer can be derived in a manner similar to that used in the discussion of the scanning Fabry-Perot interferometer of the last section. What is the wavelength of the light? The wavelengths in the visible region of the spectrum corresponding to the frequencies of exterior) the eye and is properly referred to as "light." It is not surprising that this visible region of the spectrum corresponds to the frequencies of the output of the sun. That is, ! ! ! E¡F + GE = E¿E - FG (40) The irradiance at point P is then found as ! ! IP = I0 C E¿F + GE D 2 When different field points like P¿ are considered, the emitted spiral interval dy slides along the spiral as did the contributing interval dy for the case of Syl t S 2.5 E 0.5 1.0 2.0 P• = æ 0.5 P 0.5 F 0y 0 å0.5 0 Cy) a 2.0 y a) a) 1.0 Fe æ 0.5 Y 0 yy Figure 20 Examples for Fresnel diffraction from a wire of diameter w (a) and its representation on the Cornu spiral (b). We denote the population densities of these states N1 and N2 . The problems associated with transverse vibrations of a wave in a fluid thus vanished. In some lasers, the amplifying medium consists of two parts, the laser host medium and the laser atoms. Using filtered green mercury light (l = 546 nm), directed normally on the air film between plates, interference fringes are seen. Energy may be transferred from one excited species to the other species in a process whose net effect can be symbolized by the relation A* + B : A + B*. 11 12 13 14 15 (21) Chebyshev's theorem is conventional to take both ni and ri to be positive. The appearance of a second harmonic in the polarization field can be seen by following the mathematical argument. By making the reference beam stronger than the signal beam, the minimum irradiance on the emulsion can be raised to the level of its linear response characteristics. Both are very small effects and will not be discussed further here. The width of the incident beam, finally, is assumed to be large compared with its lateral displacement due to the many reflections that contribute significantly to the resultant reflected and transmitted beams. A similar effect is produced by wrapping glossy cellophane tape around a microscope slide, allowing for regions of overlap. The narrow portion occupied by the visible spectrum is highlighted. Thus both R1 and E2 are easy to zero over very short time intervals. (a) 8.75 × 10−3 W/m2, 2.57 V/m (b) 2 × 1013 W/m2, 1.23 × 108 V/m, 0.410 T 21. Javan, Ali. In the case of these thick lens just calculated, the input plane was chosen at the left surface of the lens, and the output plane was chosen at its right surface. The linewidths of different atomic transitions vary over a wide range of values but a linewidth in the range 106 - 109 Hz for a transition associated with a photon of nominal frequency 1014 - 1015 Hz is typical. For instance, the small the pulse, the smaller the resultant amplitude A R approaches a value of 1 > 2, or half of that of the first contributing zone. Introducing the refractive indices of the media through the relation y = c>n, we arrive at Snell's law: ni sin ui = nt sin ut Fermat's principle, like that of Huygens, required refinement to achieve more general applicability. The output from a laser is primarily stimulated emission, which produces photons of nominally identical frequencies. A hologram in which the individual element of the atoms are ionized, also constitute a system that can have a continuous emission spectrum. 7 Let us suppose that as a theoretical limit, 1 bit of information can be stored in each l3 of hologram volume. O., and W. Merrier, Optical Fibre Devices (Bristol and Philadelphia: Institute of Physics Publishing, 2002). Since the dawn of modern science in the sixteenth and seventeenth centuries, light has been pictured either as particles or waves—seemingly incompatible models—each of which enjoyed a period of prominence among the scientific community. 6 During the construction of a hologram, a beam splitter is selected that makes the amplitude of the reference beam eight times that of the signal beam at the emulsion. This effect begins to be important at signal powers of only a few mW. The best values for the grating resolving power R are in the range of 105 to 106, which is one or two orders of magnitude less than the resolving powers of Fabry-Perot interferometers. The T T F W F d d d d b (a) X W W a a a b (b) Figure 15 Constructions used to determine chromatic aberration of a simple lens. Because the point light sources are "at infinity," the wavefronts of the light they emit as they fall on the aperture are plane wavefronts. The particular optical application in question may determine which method is more appropriate. New York: Halsted Press, 1987. It will be more efficient, in the general treatment that follows, to use the frequency-dependent energy density Ru(n) ... ... as determined by Maxwell's equations. 24. In this way, the component beams will be reconstructed in the imaging of the two peaks will be not more than one-half of the maximum irradiance of either peak. Thus it may be represented by f1t2 = c e -iv0t 1 , 0 0 6 t 6 2 elsewhere (11) f (t) evidently constitutes a coherent wave of the same plane. Figure 5 Finite harmonic wave train of lifetime t0 and period 2p>v0 . If B then, r = r0 cos1vt2, is proportional to the square of the frequency. Its refractive index is 1.50 and its central thickness is 5 cm. The presence of apertures in an optical system influences its image-forming properties in two important ways—by limiting the field of view and by controlling the image brightness. The surfaces are generated by rotating the pattern about the y-axis, Determine the maximum number of modes that can be supported when the wavelength is 1550 nm, revealing its fine structure, shown in Figure 14 illustrates the high-resolution performance of a Fabry-Perot instrument operated in the mode illustrated in Figure 7a. Assume, for example, that the refractive power in the vertical meridian of the cornea is greater by 1 diopter than the power in the horizontal meridian. Notice also in Eq. (12) that object distance and image distance appear symmetrically, implying their interchangeability as conjugate points. If the path difference d is much less than the coherence length lc of the laser, then interference fringes are poorly defined or absent altogether. 4 Due to quantum fluctuations, laser fields have an inherent uncertainty in the number of photons contained in the field. When a certain thickness of optically active material is inserted between analyzer and polarizer, the condition of extinction no longer exists because the E-vector of the light is rotated by the optically active medium. s¿ = - 1n1>n2)2s, and n. It is predicted that in order to detect gravitational radiation from astronomical sources, sensitivities to strains of less than 10-21 (over a detection time of about 1 ms) are required. 4 FUNCTIONS OF THE EYE To operate as an effective optical system, the eye must form a retinal image of an external object or scene, both large, nearby, or bright as well as dim light. Only in the unattainable limit of geometrical optics, where l 0, would diffraction effects disappear entirely. Since the phase difference is unchanged in this process, the new vector represents the same polarization state. Assuming that the grating is used for an incident light, what are the Airy disk radius at the screen? Aberrations In multilayer systems, a high reflector. Using this reflector, f2 is adjusted. S the beam of energy (Sign) through the surface of the beam. Sheppard, Mn 1 S ... W ... M ... Dispersion. ... ... MTF ... Optics. From the Edmund Scientific Catalogue. Appl. ... Figure 4 Typical ... in the range 10 to 40 nm, the grating ... Determine the fraction of ... 4 ... and ... the total ... Figure 9 The ... of a Michelson interferometer in which ... The angle of incidence at which ... in ... determines ... ... Schematic ... . But ... The index of ... is ... the ...

medium. Determine the thickness of the layers and the normal reflectance for light of 550 nm. 7 REFLECTION AT A SPHERICAL SURFACE Spherical mirrors may be either concave or convex relative to an object point O, depending on whether the center of curvature C is on the same or opposite side of the reflecting surface. Their positions are determined by the grating equation, in which angles are measured relative to the plane of the grating. Since energy propagates in the direction of the Poynting vector, B B B S = e0c2E * B, and since the ray direction is the same as the direction of energy flow, the extraordinary ray with velocity vB intermediate between vB and vB 7 shows the unusual refraction of Figure 12. In either case, the line image is parallel to the cylinder axis. Consider Figure 15a, in which a monochromatic parallel beam of light is incident on a prism, such that it fills the prism face. Actual resolutions may be somewhat less due to the theoretical value due to grating imperfections. (e) Gain saturation covers. If enough plates are assembled, the transmitted beam approaches a linearly polarized condition. In particular, a screen placed perpendicular to the OA axis, as in Figure 3, intercepts hyperbolic arcs that appear as straight-line fringes near the axis, whereas a screen placed perpendicular to the OA axis shows concentric circular fringes centered on the axis. 9 In an interference experiment of the Young type, the distance between slits is 0.5 mm, and the wavelength of the light is 600 nm. Notice that a lag of p>2 is equivalent to a lead of 3p>2. Evidence of phase changes and of a polarizing, or Brewster's, angle may also be seen here. Matrix Methods in Paraxial Optics Example 2 Find the system matrix for the thick lens of Figure 8, whose matrix before multiplication is expressed by Eq. (15), and specify the thick lens exactly by choosing R1 = 45 cm, R2 = 30 cm, t = 5 cm, nL = 1.60, and n = n_f = 1. The configuration now permits rapid traversal of the beam back and forth through the laser cavity, and stimulated emission occurs, producing an energetic pulse of laser radiation. Notice the direction of the OA in this assembly. 108 Chapter 4 Wave Equations 9 LIGHT POLARIZATION As we have noted, the fields associated with electromagnetic waves are vector quantities such that, at every point in the wave, the electric field, the magnetic field, and the direction of energy propagation are mutually perpendicular, with B B the direction of energy propagation being the direction of E * B. The gain medium is a 10-cm-long Nd:YAG crystal with a saturation irradiance of 2300 W>cm2. 592 Chapter 17 Figure 8 CRT display. Leighton, and Matthew Sands, The Feynman Lectures on Physics, vol. This pulse sequence provides a record of the local irradiance measured by each pixel in that row. Note that L is the beam traveling in the z-direction described by Eq. (24) is uniquely specified if the amplitude E0 , phase constant {, wavelength l, spot size at the beam waist w0 , and location of the beam waist (z = 0 plane) are known. Such a convention (recently) is called a compensator. ' The expression for Emn1x, y, z t2 given in Eq. (66) with v = 2pnmnq describes the Hermite-Gaussian modes of a laser cavity with two spherical mirrors. What is the power of the argon-ion laser? Equation (11) has the same form as the equation of motion of a driven harmonic oscillator with damping. In this case, application of the field produces some reorientation of the molecules so that, on the average, the positive end of the dipole is in the direction of the field. An B incident beam is shown, with E chosen for the moment in a direction perpendicular to the plane of incidence. The first term produces astigmatism, and the second, which is symmetrical about the optical axis, is called curvature of field. The source of the electrons may be a heated cathode (thermionic emission), a strong field applied at the cathode (field emission), or the impact of positive ions on the cathode (secondary emission). (In fact, J11x2>x tends to 1 2 as x tends to zero, so the irradiance tends to I0 as u tends to zero.) The pattern is symmetrical about the optical axis through the center of the circular aperture and has its first zero when q = 3.832, as indicated in Figure 6a and b. The difference in cavity lengths makes the frequencies of the transmission peaks of the two wavelength components for the same mode number m is d = m2>2 - m1>2 = mn2>2 The difference in cavity lengths is equivalent to the transmission peaks for wavelength component l1 is the free spectral range of the variable-length Fabry-Perot interferometer, dl/r = lm + 12l1>2 - ml1>2 + l1>2 The transmittance peak associated with the mode number m + 1 of l1 will overlap the transmittance peak with mode number m associated with 12 if cd = dlsr . In Example 2 we explore the quantization conditions for the electromagnetic field and the hydrogen atom. When the light irradiance becomes great enough, linear optics is not adequate to describe the situation. 200 Chapter 8 Optical Interferometry Cavity irradiance. When the arc is enclosed in an atmosphere of vapor at high pressure, the lamp is a compact short-arc source and the radiation is divided between the line and continuum spectra. In this case, Figure 5 Transmittance curve for the Pockels cell modulator. What is the slit separation? Assume the film is in air and light is incident at near-normal incidence. 4 RESOLUTION In forming the Fraunhofer diffraction pattern of a single slit, as in Figure 1, we notice that the distance between slit and lens is not crucial to the details of the pattern. 2 A transverse wave pulse, described by y = e. Even before developing, the emulsion contains a latent image, a distribution of reduced silver atoms determined by the variations in radiant energy received. Thus, repeated forward and backward traversals of the material by a light beam has a cumulative effect on the angle of rotation b. We turn now to cases where this constitutes an unwarranted approximation, cases in which either or both source and observation screen are close enough to the aperture that the wavefront curvature must be taken into account. From this direction the two representative E-vibrations—labeled E and E7—have dissimilar effects on the electrons in the oxygen base plane. Solution Using Eq. (23) together with Eq. (20), fn = r0 r0 R0 = = n nl nl so that fn = n ln and its quantized values is fn = 30 cm fn = 30>3 = 10 cm, f5 = 30>5 = 6 cm, and so on. The image points in a one-to-one correspondence with the azimuthal fans that pass through the same annular region lie on a circle. If a star is regarded as an extended, incoherent source with light emanating from a continuous array of points extending across a diameter s of the star (see Figure 15b), then the spatial coherent width ls in Eq. (38) becomes ls 6 1.22l u (38) Here the factor 1.22 arises from the circular shape of the source, as it does in the Fraunhofer diffraction of a circular aperture. If the effective length of the cylindrical lens is CL, then by similar triangles it follows that s = xj. AB = CL 6 To be more precise, we are speaking of a plano-convex or plano-concave cylindrical lens as shown in Figure 25. As the analyzer is rotated, the transmitted light varies in irradiance. The average power is thus Pav = Ep/T, so that Pav = Ep ¢tp T Finally, setting Pav = ECW and solving for the peak power gives Pp = T 0.001 P = 1 10 W2 * 4 * 104 W ¢tp CW 0.25 * 10-6 h. When viewed under the same conditions, the 360° hologram in Figure 4 produces a view of the fish from all sides. An average of several tries gives 5.625 cm. 6 It is important to distinguish the "order" of an electro-optic process as determined from Eq. (3) for the polarization and as determined from Eq. (7) for 1>n2 or rk. We now expect the Fraunhofer diffraction pattern to be the complex amplitude of the electric field originating with the real point source at S. The curve drawn here is the sum of the individual intensities. Fiber optic telescopes for the building towards steady-state laser action with emphasis shifted to the evolution of the light field within the optical cavity. Show how this effect might be used to correct dispersion broadening in an optical fiber. We have determined the minimum wavelength separation that can be resolved with a Fabry-Perot interferometer. (a) Lens L2 of diameter 6 cm (b) The entrance window is 12 cm to the right of L1 and has radius 9 cm. Solve for w1 to get w1 = 4.38 * 10-4 m. The integral shift of fringe patterns is then easily seen and can be combined with the monochromatic measurement of ex described previously. Assume a substrate index of 1.50 and normal incidence. The letters R and V refer to real and virtual, O and I to object and image. 9 MULTIPLE-BEAM INTERFERENCE IN A PARALLEL PLATE We turn now to the problem of reflections from a thin film, already considered in a two-beam approximation in Section 4. (a) (b) M1 (Optical Interferometry) by a spherical wave front. Our approach is to formulate the problem using the complex amplitude of the electric field originating with the real point source at S. The Sun is regarded as the Sun's irradiance at the surface of the earth? If a corrective lens is used to test the optical quality of another optical component, such as a prism, situated as shown in Figure 4b. 310 Chapter 17 Fresnel Diffraction strip is the amplitude of the electric field originating with the real point source at S. The time required for 1 ~ 10 m, in the green, the brightness has dropped to 50%. Without proof we state that the lineshape function, resulting from this process, is well described by a Gaussian function, g1n2 = a 4 ln122 pen2D b 1>2 e -4 ln122[1n - n02>cnD] 2 (51) Here, n0 is the center frequency of the emission from the atoms in their rest frame and cnD is the full width at half-maximum of the Doppler-broadened lineshape function. (b) Huygens' construction to prove the law of refraction. 1 DICHROISM: POLARIZATION BY SELECTIVE ABSORPTION B A dichroic polarizer selectively absorbs light with E-vibrations along a unique direction characteristic of the dichroic material. The point object is 15 cm from the lens. Each bundle enters at the center of curvature of the primary mirror. (17), (21), and (22), that the term in parentheses is given by 1 il 1 0m - e q w 0z pw2 (54) If we use Eq. (54) and a change in variable, j = 22x>w, in Eq. (53), we obtain analytically the Hermite differential equation, 0 2g 0j2 - 2j 0g C1w2 + q = 0 0j 2 (55) This equation is known to have a solution only if C1w2 = 2n + 1, n = 0, 1, 2, 4 (56) The solutions to Eq. (55) are the well-known Hermite polynomials, g1j2 = Hn1j2 = 1>n = [dna e-j2 fix 2x n (57) where the first few Hermite polynomials are H0 = 1 H1 = 2j H2 = 4j2 - 2 (58) 602 Chapter 27 Characteristics of Laser Beams Solution of Eq. (58) with C1 = 0, 1, 2, A gives m = 0; H01j2 = 1 m = 1: H11j2 = 2j m = 2: H21j2 = 4j2 - 2 (59) 8x2 - 2 m = 2 (59) Applying the second condition and solving for the b-expression in Eq. (52) (in, a manner identical to that for the q-expression, we obtain, using the change of variable h = 22y>w, Zw2 0h 0 2h 2h + h = 0 2h2 (60) for which the solutions are again the Hermite polynomials: h1h2 = Hn1h2 = Hn n 2p2 Ey, where n = 0, 1, 2, A (61) obtained for all h from the generating expression, Eq. (58). 509 nm 518.5 nm To an ecstatic audience. Results: 800 nm 613.9. FILM-THICKNESS MEASUREMENT BY INTERFERENCE Fringes of equal thickness provide a sensitive optical means for measuring thin films. At first glance, this sensitivity would seem unachievable since it implies that length changes eL smaller than the size of an atomic nucleus 1 ' 10-15 m2 would need to be measured in a device Quadrupole gravity wave Mirror at y-y br vit Fa ca Arm 2 Mirror P1 P0 A Mirror P0 Beam P2 P0 /4 splitter Photodetector Laser Figure 17 (a) Schematic of the LIGO interferometer. This separation of the original light into two parts, preliminary to recombination and interference, is usually referred to as amplitude division, in contrast with P n0 of C A T Transparent film R ns Substrate Figure 10 Double-beam interference from a film. The cell is filled with carbon disulfide and linearly polarized sodium light is transmitted through the cell, along the B-field direction. This is shown by the black dots. Mosby Company, 1980. Let's see how an optometrist might calculate the spectacle power required to correct hyperopic vision. An eyepiece viewing the primary image and providing further magnification merely enlarges the details of the object captured by the lens. The optical system of Figure 1b is now equivalent to the case of interference due to a plane, parallel air film, illuminated by an extended source. 19 To what diameter spot should a He-Ne laser of power 10 mW be focused if the irradiance in the spot is to be the same as the sun's irradiance at the surface of the earth? If a corrective lens is placed at the near point of an observer, the focal power required at the near point of the observer with the correction of each original zone, now subdivided into three half-period zones, adds, at the observation point P. For e0 = A, to provide one amplitude A given by 1st zone 2nd zone 1opaque2 3rd zone removed a P 4 A = 3 a1 - a2 + a3 - 5 a4 + a5 - a6 + 5 a7 - a8 + a9 - A a1 (22) Comparing the amplitude of Eq. (22) at r0 = f1>3 with the amplitude at r0 = f1 , we see that at r0 = f1 , the entire first zone (made up, effectively, of 318 Chapter 13 Fresnel Diffraction a1 , a2 , and a3) contributes, whereas at r0 = f1>3, only one of these does so. In Figure 9, a concave mirror collimates the light incident on the echelle, located near the slit and oriented with grooves horizontal. One of the most commonly used is the Glan-air prism, shown in Figure 15. After multiple reflections, the ray will leave just a large part of its energy. This may happen, for example, if the film thickness varies, and, therefore, the spatial separation of two interfering beams—such as (a) and (b)—are increased, while the pupil of the eye viewing the reflected light is limited in size. If the source of light is a laser, the fringe pattern is clearly visible on a screen placed anywhere in the vicinity of the film. What is the resolution in wave number? Equations (12) and (14) are correct for B the E and B vectors as chosen in Figure 1. (d) Photograph of the diffraction image of a rectangular aperture with n = a, as in the representation of Figure 5b. (9) and (10), implies that the ratio of the overall rate of stimulated emission to that of stimulated absorption is the ratio of the population densities of the upper and lower energy levels. The E of the elliptical wavefront is intermediate between E and E7 . To do this, we need to consider the case of an off-axis object point. As indicated in the preceding example, in this theory the wave-particle duality becomes reconciled in the sense that both classical waves (i.e., light) and classical particles (i.e., electrons) are seen to have the same basic nature, which is neither wholly wave nor wholly particle. In certain situations, wavelike attributes may predominate; in other situations, particle-like attributes stand out. Overlapping occurs because in the grating equation, the product a sin u may be equal to several possible combinations of ml for the light actually incident and processed by the optical system. Of course, the emulsion must itself possess a high-resolution potential to record faithfully such detail. The ray passes through the optical axis at O and then Q M a u F a N a u W B R Q Optical axis G u a V b a s a M K o s a (a) A x s n (a) a n 1+ = µ s n 3 + 1 A search of the Internet will reveal the existence of several free (though highly capable) ray-tracing programs. (d) Diffraction fringes from a straight line. For simplicity, we shall assume a lateral magnification of 1. For the fully tensed eye, the front surface of the lens sharpens its curvature from a radius of R = 10 mm to R = 6 mm. When the hologram is developed, it consists of grooves in the surface of the material. SUMMARY OF TERMS Brightness Aperture stop AS: Entrance pupil EnP: Exit pupil ExP: The final element in an optical system that limits the size of the cone of rays accepted by the system from an axial object point. The magnitude of b can be determined by noticing that the resultant E that determines the angle b is always the diagonal of an equal-sided parallelogram, so that u' - u = ψ + b (a) or y b = 121u' - u/P2 (9) Using Eq. (8) in Eq. (9) leads to E u u E b = 1 121k' - kP2z k F. Finally, using k' = k0n', kP = k0nP , and k0 = 2p>l0 , where l0 is the wavelength in vacuum, b = (b) Figure 19 Optical rotation produced by left- and right-circularly polarized light When spread through an active medium. At the time of this writing, members of the Laser Interferometer Gravitational Observatory (LIGO) project are building, at two distinct sites within the United States, interferometers designed to detect and study gravitational waves. Assuming that the overall efficiency of this laser system is 3%, find the pump energy required to operate this laser system. A summary of radiometric quantities and units and the corresponding photometric quantities and units are given in Table 1. New York: John Wiley and Sons, 1967. Determine the value of the complex radius of curvature q at the beam waist. What is the energy (in J and in eV) of a visible photon of wavelength 555 nm? (Recall the importance of the high-frequency components in a Fourier series when synthesizing the fine features of a function, like the corners of a square Figure 5 Optical fiber. For n = 1.50, the angle should be u = 53°. In a semiconductor, the band-gap energy is between 1 and 2 eV. Because of coma, an off-axis object point images as a blurred shape that resembles a comet with a head and a tail—hence the name "coma." Figure 8 illustrates the formation of a comatic image. In this case the contributing zones range from z = - w>2 to z = w>2 For a field point P along the SOP axis. For a resultant with amplitude A, the perpendicular component amplitudes are E0x = A cos a and E0y = A sin a. (a) 1 2 e 1 0 P 1 2 n (b) Fresnel Diffraction 319 grow down the cornea called the Cornu spiral. By Eq. (2), the nth order of interference, m = 0, occurs at um = ui , the direction of the incident light, for all l. Phase shift on reflection F Circularly polarized light 0 30 60 Angle of incidence u (a) or 30 60 Angle of incidence u (b) (TE or TM mode), external reflection (glass to air) Phase shift on reflection F Phase shift on reflection f 0 (a) TE mode, external reflection (air to glass) Incident light up 0 uc 30 60 Angle of incidence u 90 0 90 (d) TM mode, internal reflection (glass-to-air) (c) TM mode, external reflection (air-to-glass) Example 2 What is the phase shift of the TM and TE rays reflected both externally and internally for the situation discussed in Example 1? As shown in Figure 1, the waves do not arrive at P in phase. P = NerB (2) where N is the number of elementary dipoles per unit volume and e is the magnitude of the electronic charge. Notice also the distinction between the analogous terms irradiance (radiometric) and illuminance (photometric). By suppressing the gain of the higher-order modes—those with intense electric fields near the edges of the beam—the laser can be made to operate in a single fundamental mode, the TEM00 mode. We take the waves, at the superposition point P, to have the forms E1 = E01 cos1ks1 - vt + w12 E2 = E02 cos1ks2 - vt + w22 (1) (2) Here, s1 and s2 represent the directed distances measured along the propagation directions of each light wave from the reference planes at which the phases of the individual waves are w1 and w2 at time t = 0. The photopic response (rods) trails roughly from twilight to bright sunlight. M = 12>1 12 1 + b f1 f2 22 Magnification is made of two thin plano-convex lenses, each of 3-cm focal length and spaced 2.8 cm apart. When the real image falls in the focal plane of the eye lens, the magnified image is viewed at infinity by the eye located at the exit pupil. That is, the viewer "sees" the tip of an image at point P1,. The wavefronts, having been shaped by the optical system, exist in image space with refractive index n2. 2 Coherence When a laser has a high-power pulse, which was predicted in the previous paragraph to be a destructive interference between waves at P on the sphere, the circle (or disc) of light increases in size as it contacts a new spherical wave. Consider the case where e0 = 1, destructive interference yields the minimum, or background, irradiance Imin = 0 at I1 = I2 (21) (16) is a condition of a sinusoidal intensity modulated by the resistance. Of course, the sum of the squares or Airy discs. Either mode, therefore a very high relation. The diffracted light of the entire reflected amplitude is applied to the local elements (maximum) of the reference light generated from the lower-energy... Then. the resulting amplitude is produced by the recombination of electrons and holes in the vicinity of the junction. Accordingly, if the widths of the square waves are allowed to diminish, 100 terms 3 terms 10 terms E(t) Figure 3 Fourier series approximations to a square wave. What color will be transmitted by a zircon plate, 0.0182 mm thick, when placed in a 45° orientation between crossed polarizers? Notice that the new wavefront is tangent to each wavelet at a single point. Undepleted Pump Approximation It is often true that the laser pump does not significantly empty the ground state of the four-level system so that N0 ≈ N3 and N0 L N T. (For clarity, only 4 zones are shown on the vertical (focusing) section of the lens in Figure 31. Where is the far field for this laser (if one uses the criterion zFF Ú 50z0? Phillips. (a) A sin(2/(z - vt) (b) A sin(2/(z + vt) (c) A sin(2/(z/(3)(x + y + z) ± vt) 15. Further, recall that the low-loss "cavity modes" of a linear laser cavity are separated by c/2d, where d is the cavity length. To show this, let us observe the wave at z = 0 and choose wx = 0 and wy = e, so that wy 7 wx . Lens Design Fundamentals. Total Magnification When the final image is viewed by the eye, the magnification of the microscope may be defined as in the case of the simple magnifier. The fields Eb and Bb are then related to the fields Ec and Bc at the back boundary of the second film layer by a second transfer matrix. Show that in a double-slit Fraunhofer diffraction pattern, the ratio of widths of the central diffraction peak to the central interference fringe is 2(a/b), where a/b is the ratio of slit separation to slit width. These carefully numbered and carefully tested hypotheses cause the cornea to bulge or steepen in the center, increasing the refractive power of the eye. 12 The attenuation of a 10 km length of RG-19/U coaxial cable is about 12 db at 50 MHz. Suppose the input power to the cable is 10 mW and the receiver sensitivity is 1 mW. The holographic plate is situated in the Fourier-transform plane—the spectrum plane. On a 1.65 x 1.65 24 A convex thin lens with refractive index of 1.50 has a focal length of 30 cm in air. 15 Production of Polarized Light INTRODUCTION Any interaction of light with matter whose optical properties are asymmetrical along directions transverse to the propagation vector provides a means of polarizing light. The extreme possible position of the lens determines the nearest distance of objects that can be handled by the camera. New York: John Wiley and Sons, 1976. 18 Consider the transmission-variable-frequency Fabry-Perot cavity shown in Figure 15. A prism design used in spectroscopy is one that produces a constant deviation for all wavelengths as they are observed or detected. 590 Chapter 27 Characteristics of Laser Beams Front Transverse plane (x, y) O z Figure 4 The surfaces of constant phase for spherical waves are concentric spheres radiating outwardly from a point source O (Photo by Sheri Trbovich.) Metal contact Electrical lead Cleaved end Heat sink and Output electrical contact p-p type p n p-n y Input junction Figure 7 Simple p-n junction, laser diode pumped by an injection current. The factor ei12wt, when compared with the phase term in Eq. (3), indicates an angular displacement of the image direction by 2a relative to the normal to the film plane. Put another way, the images of the vertical lines in an object are located in a different plane from the images of the horizontal lines. A Q-switched laser having high gain in the cavity uses the carrier in the cathode quide 1C022 laser that emits radiation of wavelength 10.6 mm. The chord, in turn, serves as the backing for the retina. Lifetime Broadening Classically, an atom driven by a nearly resonant electromagnetic field oscillates at the frequency of the driving field. Refractive indices are given for sodium light of 589.3 nm. An amount of magnification of the images are conducive to further enhancement of the ability to discriminate between two such closely spaced spectral lines. If the two meridional planes are orthogonal to one another, one horizontal and the other vertical, say, the defect is referred to as regular astigmatism, a condition that is correctable with appropriate spectacles. A section of the plane that includes the relevant points and defines the distances r1, b, and r is also shown in Figure 5 (detail). The net path difference for waves from successive slits is then e = d 1 + e 2 = a sin u1 + a sin um (1) The two sine terms in the path difference may add or subtract, depending on the direction sum of the diffracted light. It is found that a corrective lens of power 3.5 diopters placed 1.5 cm from the eye will allow this person to view objects at infinity with a relaxed eye. A given source can be characterized by an average wave train lifetime t0 , called its coherence time. e w c l1 n1 ● w c l1 N ● w c ● L (fiber modes) travel different distances in arriving at the output. The correct approximation for a thin lens is then found by setting t = 0. By Eq. (5), the corresponding Jones vector is 'E0exiw 0 0 d = Ac d E0 = c iwy d = c E0eye A 1 y x (b) y x linear polarization along y (c) Furthermore, when only the mode of polarization is of interest, the amplitude A may be set equal to 1. The preceding integral can then be rewritten, leading to E EP = Z EA i1kr0 - vt2 e eik sin u 2R2 -s2 ds r0 L-R The integral takes the form of a standard definite integral upon making the substitutions y = s>R and q = kR sin u, where ds = dy. Fig. 6 The ratio of Figure 1 and hence, the E-P resultant Bessel function of the first kind, expressible by the infinite series J1(q) = 1 2 q Figure 4 Note also 2 = ikR2 e EA r0 i1kr0 - vt2 1 - y2 eiqy dy 21 - y2 dy = J1(q) = a EP = EA 2p n eiy2 (s2 + 22 ... #2 1 #2 #3 As can be verified from this series expansion, the ratio J1(q)2>q has the limit 12 as q : 0. Problem 11. In many typical cases the spectrum of light emitted by a gas has a continuous background overlaid with a line spectrum corresponding to particular transitions between discrete energy levels. In the case of the TV channel with a bandwidth of 6 MHz, this means that 2 * 6 MHz or 12 * 106 samples must be taken each second. Brech, Physics Department, University of Dayton.) a. Typically the extra loss for the TE mode will prevent it from lasing and so the laser output will consist only of the TM mode. The measured values for calcite are n = 1.658 and n = 1.486 for l = 589.3 nm. Although the wave amplitude decreases rapidly beyond the edge TABLE 1 CHARACTERIZATION OF SEVERAL OPTICAL FIBERS CoreCladding n0 n1 n2 wc umax N. Figure 3 is a photograph showing the distortion of fringes of equal thickness produced by a candle flame when situated in one arm of a Michelson interferometer. The measured coherence length of a thermal light source is 1.06 mm. By 1.88 1.88 1.00 Polarized light The scattered light is transmitted through the sample under electro-optic polarization, with a sensitive detector... The lens is fixed at the focal points of the aperture plane. (e) The cross... (b) Cover the aperture on which the light scatters. Figure 24 Light... 5-mm sin the... 2 2 R2 2 X 2 R2 2 ... Geometrical relationships that describe light emerging from the source, after the polarization in the Shown... Within the region in front of the transfer beam, the image of the image is a first... 1.96 of the sample solution. (a) In (b) in an ordinary beam... y... (a) ... Figure 26 Wave Equation Bands. 1 The... B ... Electron... Using the... The output... A ... 267 ... In Figure 2, a grating... Figure 3 Optical... Two consecutive reflections... The figure... Solution ... A... Interference... In the... (1), ... Determine... the case... a photon ... 511 ... 10 ... 2 ... The Planck constant; thus a ... 1.06 ... c ... of 0.00 ... at ... 3.99 ... ...

...Polarization, (a) Using Eq. ... Figure 13 Optical system consisting of two thin lenses in air, separated by a distance L. With the stop located at the lens, the image is free from distortion. Knowing that a Nd:YAG laser emits photons of wavelength 1.064 mm, determine the quantum efficiency associated with each of the four pump levels. Thus, for example, the vector C 2 D = 2 C 1 D and so represents linearly polarized light making an angle of 45° with the x-axis and with amplitude of 2 22 . Since the relative distances traveled by the two beams will, in general, differ for different observation points in the region of overlap, the phase difference d will also differ for different observation points. The light polarization rotates so as to be aligned along the long axis of the liquidcrystal molecules and so that vertically polarized light entering the twisted nematic cell exits the cell as horizontally polarized light. They may be written in matrix form as Ea i sin d Eb g1 C S = C S SC Ba ig1 sin d cos d Bb cos d (24) The 2 * 2 matrix is called the transfer matrix of the film, represented in general by M = c m11 m21 m12 d m22 (25) 480 Chapter 22 Theory of Multilayer Films If boundary (b) is the interface of another film layer, rather than the substrate, Eq. (24) is still valid. Let the magnetic field be produced by winding a solenoid directly onto the ZnS crystal at a turn density of 60 turns/cm. The pump energy and rate is sufficiently high to excite a large number of atoms from the ground state E0 to several excited states, collectively labeled E3 . Furthermore, the variable y represents the length along the Cornu spiral itself. Notice that for a photon, because of its zero rest mass, there is no distinction between its total energy and its kinetic energy. Assume that the dopant density (number of atoms per cm3) of Nd in the YAG crystal is 1020 atoms>cm3 and that the YAG crystal itself is transparent to 808-nm light. 185 Interference of Light r2Ei Ei Ei Er = rEi rEi ttEi n1 n1 n1 n2 n2 n2 Et = tEi tEi rEi rtEi tEi trEi (a) (b) Figure 21 Figures used in deriving Stokes relations. Output plane Input plane (c) where the negative sign indicates that F1 is located a distance p to the left of the input plane. In this case, aperture A is imaged through L2 to form A2¿. Accepting this result for the moment and combining it with the temporal or longitudinal coherence length lt , we conclude that there exists at any point in the radiation field of a real light source a region of space in which the light is coherent. That is, E1+1t + t2 = tEI1t + t2 + r2PF1¢z = 2d, ¢t = t2E1+1t2 (20) Using Eqs. The layers are of equal optical thickness, corresponding to a quarter-wavelength for light of average wavelength 550 nm. Far-field expressions are strictly valid only in the limit that z>z0 tends to infinity. (a) $A = 23 - s'/6$, $B = 25 + 2 - ss'/6 + s'$, $C = -16$, 3 $D = -s/6 + 1$ (b) $s' = (4s + 12)/(s - 6)$; $m = 23 - s'/6$ (c) $s' = 6\ 47$ cm; $m = -0.429$ (d) $s' = 4$ cm corresponds to second focal plane; $s = 6$ cm corresponds to first focal plane 16. In the latter case, assume that the PCM is "turned on" by initiating the pump beams at the instant the entire pulse has moved inside the PC medium. C., W. polarized. For the aperture dimension a, we write analogously, for the irradiance, as in Eq. (10), I = I0 a sin a 2 b a k where a K a b a sin u 2 (17) The two-dimensional pattern now gives zero irradiance for points x, y satisfied by either ym = mlf b or xn = nlf a where both m and n represent nonzero integral values. (This corresponds to a typical DWDM system.) 265 Fiber Optics 3 a. It is important to distinguish dispersion from deviation. Note the dimensions of the cavity region. In this state, the eye forms clear images of distant objects on the retina. The light field to be amplified is taken to have irradiance I and frequency n¿ and should be nearly resonant with the 2 to 1 transition. 592 Chapter 27 Characteristics of Laser Beams waist should be taken to have a negative radius of curvature if its reflecting surface faces the beam waist, and a mirror to the right of the beam waist should be taken to have a positive radius of curvature if its reflecting surface faces the beam waist. Find the values of b for which the fourth and fifth secondary maxima of the single-slit diffraction pattern occur. If instead the incident waves are spherical, from an axial point source at distance p from the aperture, show that the necessary modification yields Rn = 2nLl where q is the distance from aperture to the axial point of detection and L is defined by 1>L = 1>p + 1>q. Variations in film thickness, as well as angle of incidence, determine the wavelength region reinforced by interference. (a) 6.6 × 10−34 m (b) 3.9 Å 3.6 × 10−17 W 3.27 and 1.61 eV 0.024 Å; 2.7 × 10−22 kg-m/s 0.511 MeV 1.422 MeV/c (a) 1.49 × 10−18 kg-m/s (b) 4.45 × 10−16 m (c) 4.22 × 10−16 m 2.77 × 1017 3.9 × 1014 Hz to 7.9 × 1014 Hz 1.5 m 0.83 m (a) 0.3 ms (b) 0.1 m (a) 39.8 W/sr (b) 106 W/m2 (c) 9.95 W/m2 (d) 0.0195 W (a) 0.0096° (b) 8.73 × 10−8 sr (c) 76.4 W/m2 (d) 8.75 × 1010 W/(m2 · sr) Chapter 2 1. Let us consider, somewhat arbitrarily, that "good" coherence will exist over an area that is 10% of the maximum area of coherence. 519 520 Chapter 24 Nonlinear Optics and the Modulation of Light y x Unpolarized light TA Pockels crystal Linear polarizer Analyzer Figure 4 The effect of applying a halfwave voltage to a Pockels cell when the system includes a crossed polarizer and analyzer. Referring to Figure 6e and making use of the thin-lens equation, with f = 11>3.5 dipoters2 = 0.286 m = 28.6 cm and s¿ = -148.5 cm, one can solve for the object distance corresponding to the near point of the corrected eye: 1 1 1 + = s s¿ f or 1 1 1 + = s -148.5 28.6 Calculation gives s = 24.0 cm. An atom can be raised from an initial state with energy Em to a final state with energy En by absorption of a photon of frequency n¿ provided that the photon energy satisfies the approximate relation hn¿ L En - Em = hn0 . Although the middle member of Eq. (37) is valid only for an ideal four-level gain medium, the general form of the gain coefficient given as the rightmost member of that equation holds for a wide range of homogeneously broadened gain media (see Section 5), but with definitions of g0 and IS different from those given in Eqs. However, these rays are intercepted and refracted by the second surface to produce a different image, as shown. Because a 7 b, the cos2 a factor varies more rapidly than the 1sin2 b2> b2 factor. In Figure 11c, the parallel reflected rays are said to form an image "at infinity." In each case, one can show that Fermat's principle, requiring isochronous rays between object and image points, leads to a condition that is equivalent to the geometric definition of the corresponding conic section. Plot the pulse at t = 0, t = 2 s, and t = 5 s. Most detectors may be classified as being either a thermal detector or a quantum detector. With that ' convention a positive imaginary part C of E0y indicates that the Jones vector 339 Matrix Treatment of Polarization represents counterclockwise rotation. In the Littrow mount, incident light is brought in along or close to the groove face normal N¿, so that ub = ui and um = - ui , as is clear from Figure 6 and Eq. (13). Identify the state of polarization corresponding to the Jones vector c 2 d 3eip>3 and write it in the standard, normalized form of Table 1. Spherical-mirror Fabry-Perot cavities are easier to align and fabricate and have greater light-gathering power than do flat-mirror cavities. The radiant intensity Ie from a sphere radiating £ e watts (W) of power uniformly in all directions, for example, is £ e>4p (W>sr), since the total surrounding solid angle is 4p sr. The Nd:YAG system provides laser output at 1.064 mm. (a) 0.164 µm (b) 5.1 × 10−6 Chapter 24 1. Thus it controls the brightness of the image. Feldott.) 184 Chapter 7 Interference of Light fringe systems, made through a microscope. The condition for interference is just that of the two-source interference pattern, where the slit separation is the distance between virtual sources S1 and S2 . If the Pockels cell crystal is rotated until theBFA and SA are at 45° to the x- and y-axes, a vertically polarized light wave E0 incident on the crystal along the field direction has equal amplitude components on FA and SA. One's own resolution (visual acuity) can easily be tested by viewing two lines drawn 1 mm apart at increasing distances until they can no longer be seen as distinct. The light is of wavelength 541 nm with a line width of 1 Å, and the path difference is 1.50 mm. +40 cm, +30 cm, −30 cm, −40 cm 35. In part (b), assume that the fully accommodated eye differs in the following ways: The front surface of the lens is more sharply curved, having a radius of +6 mm, but the back surface remains at - 6 mm. Such a situation can occur in solids and liquids in which the myriad modes of interaction between neighboring atoms lead to a nearly continuous range of possible energies of the atoms or molecules in the material. M1 (1) (1) M3 (1 ⩽ 2) (2) BS (2) M2 Figure 5 Mach-Zehnder interferometer. 15 Standing waves are produced by the superposition of the wave y = (7 cm) sin c 2p a t 2x bd T p cm and its reflection in a medium whose absorption is negligible. As an example of the latter case, consider light propagating from one focus to the other inside an ellipsoidal mirror, along any of an infinite number of possible paths. Second, in using this description one assumes that the left- and right-circularly polarized components move through an optically active material with different velocities, yᶜ and yᴾ, respectively. Rays contributing to the image that do not pass through the optical axis are called skew rays and require three-dimensional geometry in their calculations. Referring to Figure 28, where the object lies outside the focal length fo of the objective, a real image I is formed within the microscope tube. This area, which we call the correlation, clearly depends on the choice of 1qx , qy2. If the lens index is 1.60, determine its radii of curvature. a(Q) for spherical aberration in Eq. (18) vanishes. 3 Nature of Light by the experimental fact that when two beams of light intersected, they emerged unmodified, just as in the case of two water or sound waves. In a time ¢t, the energy transported through a cross section of area A (Figure 11) is the energy associated with the volume ¢V of a rectangular volume of length c ¢t. The electric and magnetic fields in this figure can be written as E = 1E cos uxN - E sin uzN 2ei1k r - vt2 B B # B Er = 1Er cos urxN + Er sin urzN 2ei1kr r - vt2 B B # B (15) Et = 1Et cos utxN - Et sin utzN 2ei1kt r - vt2 B B # B y n2 Interface kt Bt O r kr Et ut Plane of incidence P Br ur n1 z Figure 2 Defining diagram for incident, reflected, and transmitted rays at an xyplane interface when the magnetic field is perpendicular to the plane of incidence, the TM mode. Find the new, normalized form and describe the result. Then q1z2 = z + z0R + iz0I . Solving this expression for z0 gives z0 = d2 -1 - RM1>d = 11 m22- 1 - 1-2>12 = 1 m. Since the detected power is to be zero in the absence of a strain caused by a gravitational wave, the phase shift can be written profitably as d = p + dg where dg is the phase shift induced by the gravitational wave. 8 HIGH-BIT-RATE OPTICALFIBER COMMUNICATIONS In previous sections we have discussed some of the limitations to high-bit-rate transmission through optical fibers. In the nearfield approximation, the situation is more complicated. In addition, generation and recombination noise due to statistical fluctuations of current carriers occurs in photoconductors. Angles are considered positive for all rays pointing upward, either before or after a reflection; angles for rays pointing downward are considered negative. Notice that the shorter the wave train of Figure 5, that is, the smaller the lifetime t0 , the wider is the central maximum of Figure 6. The diagram makes apparent the proper generalization of Eqs. (27) and (28), D - 1 C (29) 1n0>nf2 - A C (30) y = Similarly, one can show that w = again using the fact that Det 1M2 = AD - BC = n0>nf . Fringes of a different kind are nonetheless formed. Thus, even though we are at present interested in a single thick lens, the following description is applicable to an arbitrary optical system that we can imagine is contained within the outlines of the thick lens. In order for an assembly of atoms to amplify an incident electromagnetic field, pump energy must be supplied to the atoms in order to drive the atom out of thermal equilibrium and preferentially populate the upper energy level so that N2 7 N1 and RSt. Em. 7 RSt. Abs. On closer inspection of Eq. (27), we find that the irradiance is just a product of the irradiances found for double-slit interference and single-slit diffraction. Using Eq. (26): nm + 1 - nm = 1m + 12 c c c - m = = 2d 2d 2d 3 * 108 m>s = 5 * 108 Hz 210.3 m2 d. Do this for the profile parameter ap = 2 and repeat for ap = 10. By the law of reflection, the reflected ray PQ remains within the plane of incidence, making equal angles with the normal at P. The Verdet constant is both temperature and wavelength dependent. The total number density of gain atoms is NT = N1 + N2 + N3 . (c) Image of a pair of incoherent point sources at the limit of resolution. Further, when the cavity in a Q-switched system is made to have low loss (high Q), the system is far above the lasing threshold and so the irradiance grows more rapidly and to a larger value than in the gain-switched system. If the grating in our previous example, with 5000 grooves/cm, has a width of 8 cm, then N = 40,000 and the resolving power in the first order is 40,000. Sliding the upper wedge to the left increases the thickness of the first OA orientation relative to the second, yielding a continuously variable retardation up to a maximum, in position (b), of perhaps two wavelengths, or 4p. The presence of cladding of sufficient thickness prevents leakage, or, to put it more obliquely, negates the frustration of total internal reflection. Aberration contributes to the formation of the image because, beyond a first approximation, the ray path PQI depends on the position of point Q along the spherical surface. (20) through (23), if Er is eliminated instead of Et , similar steps lead to the following equations describing the transmission coefficient t = Et>E: tTE = Et 2 cos u = E cos u + 2n2 - sin2 u (29) tTM = Et 2n cos u = 2 E n cos u + 2n2 - sin2 u (30) Eqs. The most immediate benefits of this modification are (1) an increase in the brightness of the image due to the focusing of all the rays of light from each object point onto its conjugate image point and (2) an increase in sharpness of the image, also due to the focusing power of the lens. To a first approximation, Q-switching a laser system does not change the overall efficiency of the system. What percentage of the incident light energy is transmitted by the pair when their transmission axes are set at 0° and 90°, respectively? A variable-spaced Fabry-Perot interferometer is used to examine the doublet. t 227 Coherence so that the individual squares approached spikes, one would expect a greater contribution from the high-frequency components for an adequate synthesis of the function. 18 Fresnel diffraction is observed behind a wire 0.37 mm thick, which is placed 2 m from the light source and 3 m from the screen. Photoconductive Detectors For wavelengths in the infrared, over 1 mm, photoemitters are not available and photoconducting detectors are used. 15 The gain bandwidth of the lasing transition (that is, the width of the atomic lineshape g1n2 associated with the transition) in a Nd:YAG gain medium is about ¢n = 1.2 * 1011 Hz. Express this bandwidth as a wavelength range ¢l. Consider Figure 9. Boston: Academic Press, 1990. Relationships Between A and B Coefficients The spectral energy density in an electromagnetic field in thermal equilibrium with its surroundings at temperature T takes the form r1n2 = 8phn3 1 3 hn>kBT c e - 1 (6) [See problem 1.] In thermal equilibrium at temperature T the population densities N1 and N2 of the atoms satisfy a Boltzmann relation, N2 = e -1E2 - E12>kBT = e -hn0>kBT N1 (7) These relations can be compared to the requirements imposed by the rate equations, Eqs. (a) Frontal view showing radial cuts. Let us use as a reasonable criterion for successful discrimination between neighboring pulses that their separation dt be no less than half their period T: dt 7 T 2 or dt 7 1 2n where v is the frequency. Its range is from 4400 to 400 cm-1. The prism halves are separated in the figure to clarify its action. The configuration is sketched in Figure 4a, which shows an emerging spherical wavefront centered at S. Although there are numerous other pumps or excitation processes, we cite one more process which has some historical significance. The central maximum is a circle of light, the diffracted "image" of the circular aperture, and is called the Airy disc. (19), (21), and (22) to determine R(z) and w(z) at z = 50 m. In the last two sections of this chapter, we wish to introduce only the most basic characteristics of electromagnetic waves. The lateral magnification of an extended object is simply determined by inspection of Figure 19. 9 A positive thin lens of focal length 10 cm is separated by 5 cm from a thin negative lens of focal length -10 cm. (a) Equal focal lengths result in residual longitudinal chromatic aberration. The two endpoint corrective measures, with the appropriate positive spectacle lens in place, are indicated in Figure 6d and e. What is the other wavelength? The photon lifetime, tp , of the cavity. What should be its focal length? At any wavelength, the index for the ordinary ray is a constant, given by the lower curve, whereas the index for the extraordinary ray falls somewhere between the upper and lower curves, depending on the direction of the incident ray relative to the crystal axis. Malacara, Zacarias H., and Morales R. Returning to Eq. (34), some insight is gained by examining Figure 16, which shows representative slits of a grating illuminated by plane wavefronts of monochromatic light. Nevertheless, Kerr cells find application as high-speed shutters and as a substitute for mechanical light choppers. The waves are redirected at S1 and S2 by various means, including reflection, refraction, and diffraction. If the angle u represents the angular separation of the sources from the plane of the slits, then from the diagram, ¢ /u, where / is the distance between slits, and u s>r, where r is the distance to the sources. The integration specified by Eq. (7) is over a closed surface including the aperture but is assumed to make a contribution only over the aperture itself. An effective refractive index neff for the guided wave is defined by neff = c>yg , where yg is the group velocity. Verify that the reconstructed wavefront from the hologram of a point source produces both the real and virtual images shown in Figure 10. At the input end of the fiber-optic cable, the information to be transmitted is converted by some type of transducer from an electrical signal to an optical one. X-ray diffraction serves as a probe of the lattice structure of crystalline solids and X-ray telescopes provide important information from astronomical objects. Alternatively, the aberration may be described in terms of the deviation of the deformed wavefront from the ideal at various distances from the optical axis. Fiber Optics Communications, Experiments and Projects. This instrument, probably the most adaptable of all interferometers, has been used, for example, in precision wavelength measurements, analysis of hyperfine spectral line structure, determination of refractive indices of gasses, and the calibration of the standard meter in terms of wavelengths. The image of a given object, formed by refraction at the first surface, becomes the object for refraction at the second surface. 2 THE MATRIX METHOD When the optical system consists of several elements—for example, the four or five lenses that constitute a photographic lens—we need a systematic approach that facilitates analysis. When the slits are very close together 1a V ls2, they fall within a high coherence region and the fringes in the interference pattern appear sharply defined. Field of view Field stop FS: The real element that limits the angular field of view formed by an optical system. Now, p(z) and q(z) are general functions, as yet undetermined, that are subject to constraints imposed by Eq. (9). (27) and (28) becomes imaginary, and the equations may be written in the form rTE = rTM = cos u - i2sin2 u - n2 cos u + i 2sin2 u - n2 - n2 cos u + i 2sin2 u - n2 n2 cos u + i 2sin2 u - n2 (34) (35) The reflection coefficients can be written in polar form as r = ƒ r ƒ eif and we shall refer to f as the phase shift on reflection. PROBLEMS 1 Two plane waves are given by E1 = E2 = Write the resultant wave form expressing their superposition at the point x = 5 cm and y = 2 cm. Let the light so transmitted be intercepted by an additional lens L4, as shown in Figure 7. We consider for simplicity the spectral resolution of a pulse that is, while it exists at some point, a harmonic wave. 3p p 3l a (b) presented graphically in Figure 15 is precisely described by the following set of equations and conditions: pp , p = 0, ; 1, ; 2, Á ; N Á ; 2N Á N principal maxima occur for p = 0, ; N, ; 2N, Á for a = (33) secondary minima occur for p = all other integer values A practical device that makes use of multiple-slit diffraction is the diffraction grating. In this "strained" state, the eye is able to form clear images of nearby objects on the retina. The impressive ability of dichroic materials to absorb light strongly with B B E along one direction and to transmit light easily with E along a perpendicular direction can be understood by reference to a standard experiment with microwaves, illustrated in Figure 3. The experimental observation that light can be polarized is, therefore, clear evidence of its transverse nature. Then for times t 7 t0 , Eq. (21) simplifies to 213 214 Chapter 8 Optical Interferometry + + E01 1t + t2 = r2E01 1t2 (44) If, during one round-trip time t the change in the complex field amplitude + E01 is small compared to the amplitude itself, a Taylor series approximation can be used, + + E01 1t + t2 L E01 1t2 + t d + E 1t2 dt 01 Using this in Eq. (44) and rearranging terms gives d + 1 + E011t2 = - 11 - r22E01 1t2 t dt One can verify by direct substitution that the solution to this differential equation is + + E01 1t2 = E01 1t02e-11>t211 - r 21t - t02 2 The right-going irradiance I+ in the cavity is proportional to the square of the magnitude of the complex field amplitude of the right-going wave, so I+1t2 = I+1t02e-12>t211 - r 21t - t02 K I+1t02e-≠1t - t02 2 That is, the cavity irradiance decays at the rate ≠ = 2 11 - r22 t (45) This sensible result indicates that, for lossless mirrors, the fractional irradiance loss ≠t during each round-trip time t is approximately 211 - r22 = 2t2. points such that each ray contacting a wavefront represents the same transit time of light from the source. This is amply demonstrated in the summary and comparison provided in Table 1. (c) General superposition; the amplitude of the resultant wave is neither the sum nor the difference of the amplitudes of E1 and E2 . When we use photometric quantities, then, we are measuring the properties of visible radiation as they appear to the normal eye, rather than as they appear to an "unbiased" detector. In general, however, two rays incident at the interface, as in Figure 21b, each result in a reflected and a transmitted ray, all of which are shown, with appropriate amplitudes, in Figure 21c. 4 Assume that aluminum has one free electron per atom and a static conductivity given by 3.54 * 107> Æ-m. New York: McGraw-Hill Book Company, 1972. Microwaves Beyond infrared radiation we find microwaves, with wavelengths from 1 mm to 30 cm or so. Interference fringes are seen in the overlap region on the screen. In this introduction we limit ourselves to a basic description of how apertures can affect both image brightness and field of view. In such a case we say that the sources are mutually incoherent and the detected irradiance will be I = I1 + I2 Mutually incoherent beams It is often said, therefore, that light beams from independent sources, even if both sources are the same kind of laser, do not interfere with each other. A glucose solution of unknown concentration is contained in a 12-cm-long tube and is found to rotate linearly polarized light by 1.23°. Some rays leaving O do not reach I due to reflection losses at refracting surfaces, diffuse reflections from reflecting surfaces, and scattering by inhomogeneities in transparent media. In a high-power laser, the cooling system is an essential part of the system. 28 Consider a Mach-Zehnder fiber demultiplexer depicted in Figure 16b. If the maximum irradiance produced by the fringes is 100 on an arbitrary scale, what is the difference between maximum irradiance and background irradiance on this scale? The reverse-biased external voltage increases the electric field in the junction region, which in turn increases the rate at which the electrons and holes generated by absorption of the incident radiation are swept out of the junction region. 251 Fiber Optics A more careful analysis indicates that single-mode performance results even when 2.4 d 6 (11) l p1N. Solution Substituting into Eq. (12), VHW = 0.01 212212.4 * 10-12210.032 = 26.4 kV Thus the Kerr cell behaves as a half-wave plate at a voltage of around 26 kV, considerably higher than for a typical Pockels cell. (b) 7.50 ×; 8.70 × 29. Determine the radii of the first and tenth dark rings. Objective Ocular ExP VO a a a fe fo E nP Figure 32 Galilean telescope. Because of this periodicity, increasing all x by l should reproduce the same wave. In Figure 1a, the ExP is the real image of the EnP; in Figure 1c, it is the virtual image. For any one mode, the angle of propagation is a function of the wavelength. 9 What minimum thickness should a piece of quartz have to act as a quarter-wave plate for a wavelength of 5893 Å in vacuum? The compromise surface between the S and T surfaces is indicated by the dashed line. Macleod, H. We consider several applications of Eq. (22), beginning with the following example. (Here m = 2d>l, where d is the length of the Fabry-Perot interferometer.) t1 t9 t2 t3 t4 t5 Coherence INTRODUCTION The term coherence is used to describe the correlation between phases of monochromatic radiations. Laser light is generated in laser cavities, which often take the form of two highly reflecting mirrors surrounding a gain medium. 2p T v 0 t0 2 t0 t0 2 t 229 Coherence The frequency spectrum g1v2 is calculated from Eq. (8), with the specific function f(t) of Eq. (11), +t >2 +q 0 1 1 f1t2eivt dt = ei1v - v02t dt 2p L- q 2p L-t0>2 g1v2 = Integrating, we have g1v2 = c g1v2 = +t0>2 ei1v - v02t d 2pi1v - v02 -t0>2 ei1v - v02t0>2 - e-i1v - v02t0>2 1 c d p1v - v02 2i or, after using the identity, eix - e-ix K 2i sin x g1v2 = sin[1t0>221v - v02] t0 sin[1t0>221v - v02] = e f p1v - v02 2p [1t0>221v - v02] (12) Calling u = 1t0>221v - v02, we then have g1v2 = 1t0>2p2[1sin u2>u]. To treat the initial growth of the laser field, Eq. (55) can be rectified by replacing the factor Np in the last term on the right with the factor 1NpVc + 12>Vc . Treating the cornea as a thin surface (whose own refraction can be neglected), bounded by air on one side and aqueous humor on the other, determine the refractive power of the corneal surface. Interference fringes appear in the region of overlap. In addition, there can be environmental factors that cause the center frequencies of each of the atoms in an assembly of atoms to differ from one another. The circle of light at the center corresponds to the zeroth order of diffraction and is known as the Airy disc. Now the direct image of the object and the holographic image are slightly different, and the light forming the two images interferes, producing fringes that measure the extent Figure 7 Example 1. In Eq. (20), when Rn is fixed, n increases as r0 decreases. Of course, the films must be thin enough to be partially transmitting. The schematic eye shown corresponds to its relaxed state. The directed distances s1 and s2 are the perpendicular distances from the reference planes to the point of superposition. The object is first defined mathematically by specifying its coordinates and the intensity of all its points. Virtual fringes of equal inclination may be seen by looking into the beam splitter along ray 4, with the eye or a telescope focused at infinity. The first three orders of diffraction are most commonly used. 557 Laser Operation b. The anastigmat camera objective is designed to take advantage of this. In each case, after reflection, this ray is labeled 3¿. Excessive vignetting may make the image of a point appear astigmatic. Even though object points are imaged as points, distortion shows up as a variation in the lateral magnification for object points at different distances from the optical axis. 236 Chapter 9 Coherence we may now delineate the following special cases: 1. 685 lm 650 700 750 V(): Luminous efficiency spectrum. Take into account the results of problem 5. Note that the inversion is always negative and decreases in magnitude as the irradiance of the light incident on the medium increases. Of course, for the straight edge depicted in Figure 14a, only those zones above the physical edge contribute light to a given field point. The figure defines the symbols and shows the geometrical relationships that lead to ray-tracing equations for a meridional ray. For normal incidence, bright fringes satisfy Eq. (36), ¢ p + ¢ r = 2nt + ¢ r = ml where t represents the thickness of the air film at some point. For our present purposes, it will be sufficient to show how the appropriate equations for meridional ray tracing can be developed and how they can be repeated in stepwise fashion to follow a ray through any number of spherical refracting surfaces that constitute an optical system. The scattered light at v is elastic or Rayleigh scattering. The diagram defines quantities used in applying boundary conditions to write Eqs. The left member is 1nR + inI22 = 1n2R - n2I2 + i12nRnI2 (35) The right member can also be written as the sum of a real and imaginary part. In this so-called photovoltaic mode of operation, depicted in Figure 5a, a change in the amount of incoming light leads to a change in the open-circuit voltage across the p-n junction. The fiberscope consists of a bundle of such fibers, end-equipped with objective lens and eyepiece. As indicated by Eq. (29), the finesse of a Fabry-Perot cavity depends only on the reflection coefficient r of the cavity mirrors. Determine its cardinal points and make a sketch to scale. Thus an electric field directed from the n-type to the p-type material is created in the junction region. Still, the presence of anisotropic binding forces along the x- and y-directions leads to, for light propagating along the z-direction, different dispersion curves (like that of Figure 8) for refractive index nx corresponding to Ex-vibrations and ny corresponding to Ey-vibrations. Harmonic wave functions are then adapted to represent electromagnetic waves, which include light waves. The first good replica grating usually serves as a submaster for the routine production of other replicas. According to the notion A A A A vt vt B B B B Figure 2 Illustration of Huygens' principle for (a) plane and (b) spherical waves. On the basis of spreading due to diffraction alone, how far must it travel to double its diameter? The direction of polarization is the z-direction. −17.7 cm 20. The dependence of g1t2 on t0 is now derived, under the assumption that t0 represents a constant coherence time rather than an average. A phase-conjugate mirror handles all cases and also responds to instantaneous changes in the incident wavefront. In this case, the light wave is diffracted in a way similar to that of X-rays from crystalline planes in Bragg scattering (the Bragg regime). The beam splitter in this position enables light to strike the film at normal incidence, while at the same time providing for the transmission of part of the reflected light into the detector (eye). Portions of other conversations can be carried in these pauses in order to increase the carrying capacity of the system. 8 LASER TYPES AND PARAMETERS To this point we have examined the basic processes involved in the interaction of light with matter, identified the essential parts that make up a laser, described in a general way how a laser operates, and studied the characteristics that make lasers such a unique source of light. Moreover, from the general equation of an ellipse, we have a Ey 2 Ey Ex 2 Ex b + a b - 2a ba b cos e = sin2 e E0x E0y E0x E0y (12) For this example, the equation of the ellipse is E 2y E 2x + - 0.267ExEy = 0.2 9 5 When Ex lags Ey , the phase angle e becomes negative and leads to the Jones vector (with A and C positive numbers) representing a clockwise rotation instead: ' E0 = c A d B - iC E0y a E0x Ex Figure 7 Elliptically polarized light oriented at an angle a relative to the x-axis. In the present discussion we B B choose to write the fields E1P and E2P being superposed at point P in terms B of the field ES at the sourceBpoint S. We close this chapter with an introductory glance at the electromagnetic spectrum and a survey of the radiometric units we use to describe the properties of electromagnetic radiation. Table 1 is meant to serve as a convenient summary that can be referred to when needed. These fringes reveal imperfections in the optical system that cause variations in optical-path length. The positions of all six cardinal points are indicated in Figure 3. Photography by holography is a twostep process. Know that some techniques used in near-field microscopy allow one to surpass the diffraction-limited resolution just discussed. 23 Newton's rings are formed between a spherical lens surface and an optical flat. Note that gth characterizes the cavity losses. Some of the fibers function as light pipes, transporting light from an external source to illuminate inaccessible areas internally. Wavelengths extending further into the infrared can be handled by prisms made of salt (NaCl, KCl) and sapphire 1Al2O32. The central ray makes angles of u1 and u2 , respectively, relative to the area normals, as shown. In making a hologram with a microscope, the specimen is illuminated by laser light, part of which is first split off outside the microscope and routed independently to the photographic plate, where it rejoins the subject beam processed by the microscope optics. What is the maximum crystal thickness useful in generating second harmonic light? The thick lens can be treated by methods you should already be familiar with. Since points along the plane wavefront do not arrive at the interface simultaneously, allowance is made for these differences in constructing the wavelets that determine the reflected wavefront. Check your results against Figure 3. In view of the unique role played by the eye in human vision, it is not treated in this chapter. Then, by Eq. (41), EA = - EB and IA = IB at the point. If the crystal is rotated about the incident ray direction, the extraordinary image is found to rotate around the ordinary image, which remains fixed in position. With the stop located between object (far right) and lens, barrel distortion occurs in the image. The diffracted light is observed on a screen at 15 cm farther along the optical bench. Consider next that the O¿ system, together with the pulse, moves to the right along the x-axis at uniform speed y relative to a fixed coordinate system, O(x, y), as in Figure 1b. Light from a point object is incident on the concave, cylindrical surface from a distance of 25 cm to the left of the lens. If this region is illuminated with monochromatic light, the light diffracted from the deformations can be photographed and converted into a visual image of the underwater object. The points P represent the position of the resultant. That is, an energy of 13.6 eV must be given to an electron in the ground state of hydrogen in order to ionize the hydrogen atom. Kingston, R. We do so in the following subsections. This discussion should make it clear that high-quality microscopes today are designed as a whole and usually for a specific use. The image provided by the hologram may be viewed by focusing at leisure on any depth of an unchanging field. Since a cylinder has no curvature along its axis of symmetry, the surface has no power in the horizontal meridian. For the case of arbitrary N, there will be N - 1 zeroes and N - 2 secondary peaks between principal maxima. The oscillating dipoles, consisting of electrons accelerating in harmonic motion, are tiny radiators—antennas that reradiate or scatter energy in all directions except along the dipole axis itself. Any device that produces a measurable physical response to incident radiant energy is a detector. 35 An airplane is used in aerial surveying to make a map of ground detail. Find the equation of the intersection of the oval with the xy-plane, where the origin of the coordinates is at the object point. Rather when this condition holds, the cavity loss per round-trip exceeds the gain per round-trip and no irradiance builds up in the cavity. For longer distances, this leads to a modified dependence of the form, dt r 2L . The "negative" of a hologram alters neither fringe contrast nor spacing and hence does not modify the stored information. Example 1 Consider a Ronchi ruling with slits of width 0.1 mm illuminated by light of wavelength 488 nm. Example 4 Suppose that each lens on a pair of binoculars has a diameter of 35 mm. (b) Equivalent optics for the Michelson interferometer. The mean wavelength is 6328 Å. Now the phases B B of the ᶜ- and ᴾ-components, Eᶜ and Eᴾ respectively, are not equal. In this chapter, we first describe the basic processes involved in the interaction of light with matter and discuss the nature of light emitted by nonlaser light sources. (What is the ratio of a/b in this case? The image of the object in the aperture plane is thus superimposed over the pattern on the partially transparent mask. Consider a 1200-groove/mm grating to be blazed for a wavelength of 600 nm in first order. The slits are 0.04 mm in width and separated (center to center) by 0.25 mm. The lens refractive index is 1.50. Sources operating at or near this wavelength are thus ideal in reducing pulse broadening and increasing transmission rates. Visibility is enhanced in (b), where the background irradiance Imin = 0 when I1 = I2 . Determine the visibility of the interference fringes. The fiber may be, typically, a glass or plastic filament 50 mm in diameter. (7) and (11), as follows: Eb = Et1e -id + Ei1eid = Et2 (18) Bb = g11Et1e -id - Ei1eid2 = gsEt2 (19) Disregarding for the moment the rightmost members, these equations may be solved simultaneously for Et1 and Ei1 in terms of Eb and Bb , yielding Et1 = a g1Eb + Bb id be 2g1 (20) Ei1 = a g1Eb - Bb -id be 2g1 (21) Finally, substituting the expressions from Eqs. The displacement at the nodes is always zero. In this section we discuss two such effects, the Pockels effect and the Kerr effect, and show that these effects can be used in light modulators. Determine the wavelength of the light. The rate of spontaneous emission is, of course, still given by Eq. (3). An Introduction to Modern Optics. Notice that since EnW and ExW are both images of the FS, they are conjugate planes. Since the ellipse is the locus of all points whose combined distances from the two foci is a constant, all paths are indeed of equal time. Since rays from O, directed toward this virtual aperture, make a smaller angle 1N¿ON2 than rays directed toward the lens edge 1L¿OL2, this virtual aperture serves as the effective entrance pupil for the system. Then, using Eq. (13), p p p 2 E20 = c7 sin a b + 12 sin a- b + 20 sin a b d 3 4 5 p p p 2 + c7 cos a b + 12 cos a- b + 20 cos a b d 3 4 5 or E20 = 9.3332 + 28.1662 and E0 = 29.67. According to Eq. (35), the phase difference between successive reflected beams is given by d = k¢, where ¢ = 2nft cos ut (44) If the incident ray is expressed as E0eivt, the successive reflected rays can be expressed by appropriately modifying both the amplitude and phase of the initial wave. The scattering is called Brillouin scattering and is another third-order effect that does not require a medium possessing inversion symmetry. These dipole oscillations generate electromagnetic radiation of angular frequency 2v, which is present in the resultant field, together with the stronger first-order field at the fundamental frequency v. Photographs of diffraction fringes produced by 2, 3, 4, and 5 slits are shown in Figure 17. It must provide a large field of view, in the range of 35° to 65° for normal lenses and as large as 120° or more for wide-angle lenses. Notice that in this case six cavity modes are at frequencies that have gain larger than the threshold value. Calculate the reflectance R for the TE mode when the light is incident from air onto glass of n = 1.50 at the polarizing angle. As the aperture approaches the lens, it permits a shorter average distance to the lens. 22 A quasar near the limits of the observed universe to date shows a wavelength that is 4.80 times the wavelength emitted by the same molecules on the earth. When the film is developed, straightline fringes appear. As with the Pockels cell, a modulating voltage produces phase modulation that is converted to amplitude modulation by the polarizer-analyzer pair. Let the actual irradiance over the image plane be given by Ii1X, Y2. In this discussion we are content to present briefly the radiometric quantities or physical terms used to characterize the energy content of radiation. In this form, show that the superposition of the waves is the standing wave given by Eq. (22). Gamma Rays This type of EM radiation has its origin in nuclear radioactive decay and certain other nuclear reactions. This description rests first on the fact, demonstrated in the previous chapter, that linearly polarized light can be assumed to consist of equal amounts of leftand right-circularly polarized light. They derive their name from the manner in which they are seen to float in one's field of view, when one looks or squints at a white ceiling, for example. Notice that rays from O, directed toward the edges of EnP, are in fact first refracted by the lens so as to pass through the edges of the real aperture stop. The single hole, used to secure a degree of spatial coherence, may be eliminated if laser light, both highly monochromatic and spatially coherent, is used to illuminate the double slit. 20 18 n1 2 16 14 n1 1.8 R (%) 12 10 8 n1 1.6 6 4 n1 1.4 2 n1 1.2 0.1 22 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0 Path difference/wavelength Theory of Multilayer Films INTRODUCTION The physics of interference in single-layer dielectric films, in its essentials, should already be familiar to you. If the point object is only 6 cm from the lens, describe the line image. Let f1 = 15 cm, f2 = 15 cm, and their separation be 60 cm. What focal length for the negative lens gives a flat Petzval surface? Show that a(Q) also vanishes for s¿ = R and for rays intersecting with the spherical surface vertex. In this chapter we develop a transfer matrix to represent the film and characterize its performance. Thus, the wave they generate is not out of phase with respect to the incident wave, and complete cancellation of the forward wave does not occur. Formation of constructive fringes in a holographic grating. A typical arrangement for viewing these fringes is shown in Figure 15a. Find the irradiance of these optical electromagnetic B waves and the amplitude of their E-field at a distance of 10 m from the lamp. We content ourselves for purposes of this discussion with pointing out that optically active materials possess molecules or crystalline structures that have spiral shapes, with either left-handed or right-handed screw forms. That is, the phase fronts are nearly planar and parallel in this region. What is IP>Imax at the first principal maximum? Example 4 a. Typically, the record of the irradiance of each pixel is stored digitally. (1) through (3), we have dEP = a a ES ik1r + r¿2 -ivt be e dA rr¿ (5) The field at P due to the secondary wavelets from the entire aperture is the surface integral of Eq. (5), EP = aESe -ivt O a 1 ik1r + r¿2 be dA rr¿ (6) Aperture Equation (6) is incomplete in two ways. Spectral reflectance curves for N = 2 and N = 6 double-layer stacks have been calculated and plotted in Figure 9. Adding Eqs. H., ed. In the case of solutions, the specific rotation is defined as the rotation due to a 10-cm thickness and concentration of 1 g of active solute per cubic centimeter of solution. Consider the first coherence time interval t0 , in which the pulse function may be expressed by w1t2 - w1t + t2 = e 0, H1, 0 6 t 6 1t0 - t2 1t0 - t2 6 t 6 t0 235 Coherence In successive intervals, the expression is similar, except for the value of H1. The disadvantages of this restriction can be overcome if the photograph is a hologram, which in a single snapshot contains potentially all the ordinary photographs that could be made after successive refocusings throughout the depth of the living specimen. To take advantage of the maximum resolution, the light must cover the entire ruled width of the grating. Where must a small object be positioned so that light from the object is rendered parallel by the combination? If the two refracted rays, linearly polarized perpendicular to one another, can be physically separated, then double refraction can be used to produce a linearly polarized beam of light. The use of the Fabry-Perot cavities in the interferometer arms increases the sensitivity of the device by a factor roughly equal to the number of round-trips in a photon lifetime of the Fabry-Perot cavities. What is its beam-spread angle in the far field? We summarize his approach in what follows. The order of the interference pattern is indicated by m, with integral values of m determining positions of fringe maxima. We wish now to introduce some of the mathematical formalism and terminology commonly used to discuss Fourier transformations in another approach to imaging. Forces are exerted on the charges by the electric field of the waves and, because of the motions of the charges, also by the magnetic field of the waves. (2) Polarizing angles exist for both external reflection 1n2 7 n12 and internal reflection 1n2 6 n12 and are clearly not the same. 510 Nonlinear Optics and the Modulation of Light 1 THE NONLINEAR MEDIUM Nonlinear phenomena are due ultimately to the inability of theBdipoles in the optical medium to respond in a linear fashion to the alternating E-field associated with a light beam. Finally, we will assume that the four-level system is closed, in the sense that all atoms in the sample exist in one or the other of these four levels so that NT = N0 + N1 + N3 + N4 5 See problem 7 for another common arrangement involving three levels. The angle of inclination is determined from tan 2a = (10) E 20x - E 20y E0y = 2B2 + C 2 , and e = tan-1 a C b B (11) Example 1 Analyze the Jones vector given by c 3 d 2 + i to show that it represents elliptically polarized light. The Q of the cavity is rapidly switched to a high value so that the loss rate of the cavity is reduced to a low value. 100 Chapter 4 Wave Equations 4 HARMONIC WAVES AS COMPLEX FUNCTIONS Using Euler's formula, it is possible to express a harmonic wave as the real (or imaginary) part of the complex function ' y = Aei1kx - vt2 (18) so that ' y = Re 1y2 = A cos1kx - vt2 or ' y = Im 1y2 = A sin1kx - vt2 (19) ' Note that any equation that involves only terms that are linear in y and its de' ' rivatives will also hold for y = Re 1y2 or y = Im 1y2. Example 4 Convex (a) A thin plano-cylindrical lens in air has a radius of curvature of 10 cm, a refractive index of 1.50, and an axial length of 5 cm. The coherence length of this radiation, by Eq. (17), is 78 cm! Laser radiation has far surpassed even the coherence of this gas-discharge source. "Optical Interferometry of Surfaces." Scientific American, July 1991: 66. The peak response at 5500 Å closely matches the response of the human eye. With the appropriate cylindrical surface ground on the rear of the spectacle lens, the correction of - 1.00 D reduces the power in the vertical meridian from 46.00 D to 45.00 D, thereby equalizing the refracting powers in the two meridians and negating the corneal astigmatism. This is accomplished by exciting (or pumping) more atoms into the higher energy level than exist in the lower level. How many half-period zones are contained in an aperture with a radius 100 times larger? The construction makes clear the equivalence between the angles of incidence and reflection, as outlined in Figure 4a. s1 To simplify notation we introduce the constant phases, a1 = ks1 + w1 (3) a2 = ks2 + w2 (4) The time variations of the EM waves at the given point can thus be expressed by E1 = E01 cos1a1 - vt2 (5) E2 = E02 cos1a2 - vt2 (6) Two such waves, intersecting at the fixed point P, differ in phase by a2 - a1 = k1s2 - s12 + 1w2 - w12 due to a path difference, given by the first term, and an initial phase difference, given by the second term. 1pR2a22>4 pa2 = , independent of the value of R. A change from low-level light or scotopic vision to high-level light or photopic vision in the process of adaption consists of a rapid bleaching out of rod pigment and a resulting insensitivity of the rod receptors. Such asymmetry leads to different refractive powers and, consequently, to image formation at different distances from the cornea, resulting, of course, in blurred vision. The refractive index of the lens is 1.52. Where does the fish appear when viewed through the lens? The last term depends on an interaction of the waves and is called the interference term, I12 . The retardation action due to an applied voltage V is suggested by an on-axis separation of the polarized components transmitted by the fast and slow axes of the crystal. Diffraction is often distinguished from interference on this basis: In diffraction phenomena, the interfering beams originate from a continuous distribution of sources; in interference phenomena, the interfering beams originate from a discrete number of sources. If the focal lengths for red and blue light are made unequal, such that they produce a single focus (Figure 14b), the difference in fB [illegible]

window, twice the object size 13.0 cm +20 cm or −20 cm 22.5 cm behind the lens; 1.50 times the actual size (a) −6.7 cm (b) −10 cm or −60 cm (c) 3.33 mm in front of the objective (b) erect and magnified Final image between lens and mirror at 21/34 f from lens, virtual, inverted, and 171 the original size 23. 8 LASERS AND THE FABRY-PEROT CAVITY Laser cavities typically consist of two highly reflecting spherical mirrors and so have the same basic structure as spherical-mirror Fabry-Perot cavities. Since, for this waveform, the wave disturbance at an arbitrary point in space, defined by the vector Br in Figure 6a, is the same as for the point x along the x-axis, where x = r cos u. m 1 Grating N 40,000 f Figure 14 Problem 6. This characteristic is exploited in a liquid-crystal display (LCD). This state of total darkness is referred to as the electromagnetic vacuum. Depending on the relative magnitudes of the refractive indices, the appropriate refracting surface is either a hyperboloid 1ni 7 no2 or an ellipsoid 1no 7 ni2, as shown. When conditions of enhancement, or constructive interference, and diminution, or destructive interference, alternate in a spatial display, the interference is said to produce a pattern of fringes, as in the double-slit interference pattern. 40. 278 Chapter 11 Fraunhofer Diffraction I I0 g ⩾5 k D sin u 2 5 (a) (c) 1st Maximum st 1 Zero 2 I/I0 (2 J1 (g)/g)2 0 1 3.832 0 nd Maximum 5.136 0.0175 nd Zero 7.016 0 rd 3 Maximum 8.417 0.00416 rd 3 Zero 10.173 0 4th Maximum 11.620 0.00160 4th Zero 13.324 0 2 (b) Figure 8 Circular aperture diffraction pattern. This situation is illustrated in Figure 6. We look for a procedure that will allow us to calculate the height and slope angle of the ray at any point in the optical system, for example, at point T, a distance x7 from the mirror. When the two systems come to a common temperature, the rates of energy flow between the systems become equal. These fringes will be straight, oriented parallel to the line that represents the intersection of M1¿ and M2. We see that the size of the field imaged by the optical system is effectively determined by the entrance window and, actually, by the size of the field stop. Let us adopt again the ring cavity model used earlier. Thus, 10 + s11œ = -110 yields s2œ = - 5 cm. Subscripts 1 and 2 refer to refractions at the first and second surfaces, respectively. Let us set r = r0 for the wave from the center of the slit (at s = 0). At the critical angle, sin u = n and cos ut = cos190°2 = 0. Today, Vol. Thus optical phase conjugation can be viewed as a unique type of reflection, and we refer to the nonlinear medium that creates the phase conjugate wave as a phase conjugate mirror (PCM). High-pressure and high-current operation generally results in a continuous spectral output, in addition to spectral lines characteristic of the vapor. Here, ¢k = k2v - 2kv . A = n RL t + 1, B = nnt , L 1 L 616 Answers to Selected Problems C= nL −n′ n′ R2 − nL′R − n −n 1 ′ (nL −n)(nL −n′) n′ nL t , R1 R2 D = nn′ + (nL′R) nnt 2 L 21. The result is a wave train of finite length, such as the one pictured in Figure 5. Instead, external fields can be used to perform a periodic poling of a nonlinear ferroelectric material or a nonlinear polymer. When v v0 , near resonance, the vibrations are large. The variation of lmax , the wavelength at which Ml peaks, with the temperature can be found by differentiating Ml with respect to l and setting this equal to zero. Figure 8 shows the basic Littrow mount, where a single focusing element is used both to collimate the light incident on the plane grating and, in the reverse direction, to focus the light onto the photographic plate placed near the slit. Finally, since n and ut are related to u through Snell's law, sin u = n sin ut , ut may be eliminated using n cos ut = n 21 - sin2 ut = 2n2 - sin2 u (26) The results are then rTE = Er cos u - 2n2 - sin2 u = E cos u + 2n2 - sin2 u (27) 496 Chapter 23 Fresnel Equations rTM = Er - n2 cos u + 2n2 - sin2 u = E n2 cos u + 2n2 - sin2 u (28) Returning to Eqs. In fact, it is the stimulated emission rate and can be compared to the spontaneous emission rate A 21 . Note that the rate of stimulated absorption is proportional to B12 , the irradiance I of the incident field, the lineshape function evaluated at the frequency of the input field g1n¿2, and the population density N1 of the lower of the two levels involved in the transition. As the driving frequency approaches the resonance frequency v0 of the oscillator, the amplitude of the vibrations becomes very large and subsides again as the frequency increases beyond v0 . Harmonic wave disturbances emanating from a point source in a homogeneous medium travel at equal rates in all directions. 0.01909 11. The cardinal points are located, approximately to scale, in Figure 15. Thus the beam waist is at Mirror 2. (12) and (14) appear with a change of signs. Short sections of pumped erbium-doped fiber can be placed at widely spaced (100 km) sections of a long-haul fiber-optic communications system. When all constant (or approximately constant) terms are taken out of the integral and included in an overall constant C0 , Eq. (7) is simply EP = C0e -ivt O eikr dA which is a statement of the Huygens-Fresnel principle. A = 0. Tiny bubbles or imperfections in a glass lens, for example, produce undesirable diffraction patterns when transmitting laser light. Individual phasors are shown in (a) and the resultant phasors at each step in (b). Here yf = Ba0 implies that yf is independent of y0 , so that all rays departing the input plane at the same angle, regardless of altitude, arrive at the same altitude yf at the output plane. Modal distortion can be lessened by reducing the number of propagating modes. Widths of energy levels in atoms vary greatly but a typical value is on the order of 10-7 eV. The plane portion of the wavefront in the slit opening represents a continuous array of Huygens' wavelet sources. The reflected and transmitted waves in Figure 1 can be expressed, respectively, in forms like that of the incident wave of Eq. (1): B B B B B B # B Er = E0rei1kr r - vrt2 # (2) B Et = E0tei1kt r - vtt2 (3) In the boundary plane xy, where all three waves exit simultaneously, there must be a fixed relationship between the three wave amplitudes (and thus their irradiances) that has yet to be determined. Figure 16 shows a single, representative step in the ray-tracing analysis. To produce this wave with ordinary mirrors, we would need to construct a mirror surface that matched exactly the wavefront of the incident wave at the instant of reflection. The diffraction pattern is observed q = 30 cm from the slit. Sketch the setup. In constructing ray diagrams, as in Figure 22, observe that, except for the central ray (ray 3), each ray refracted by a convex lens bends toward the axis and each ray refracted by a concave lens bends away from the axis. Teich, Fundamentals of Photonics (New York: John Wiley & Sons, Inc., 1991), Ch. 6. When the observation point is below the axis, ¢y is placed along the upper spiral. Because the gravitational force is so weak, gravitational waves coming from even the most dramatic astronomical events like the collision of black holes or the explosion of supernovae lead to extraordinarily small effects on earth. v = −0.917c 1. The central ray arrives at point O in the image plane. When specimens of cells or microscopic particles are viewed conventionally under high magnification, the depth of field is correspondingly small. Rather, the photon energy must be within a very small range of energies, near the nominal energy difference of two levels, in order to interact with the atom. At a given instant, the surfaces of constant phase for a spherical wave are given by the simple relation kr = constant Spherical wave (29) u1 w01 z w02 u2 z0 3 Note that the far-field divergence angle, as we define it, is the half-angle spread of the beam. What is the thickness of the etalon? S(y) 1.5 2.5 0.5 E 2.0 1.0 y 0.5 ⩾0.5 ⩾0.5 C(y) ⩾0.5 E⬘ ⩾2.5 13 0.5 ⩾2.0 y ⩾1.0 0 ⩾1.5 Fresnel Diffraction INTRODUCTION You should be familiar with Fraunhofer diffraction, situations in which the wavefront at the diffracting aperture may be considered planar without appreciable error. A simpler but equivalent optical system, having a single optical axis, can be drawn by working with virtual images of source S and mirror M1 via reflection in the BS mirror. The rest mass energy is mc2 = 19.11 * 10-31 kg213 * 108 m>s22 = 8.19 * 10-14 J. (2) and (3) in Eq. (1) gives, for the complex field E, ' E = E0xei1kz - vt + wx2xN + E0yei1kz - vt + wy2yN which may also be written ' ' E = [E0xeiwxxN + E0yeiwyyN]ei1kz - vt2 = E0ei1kz - vt2 (4) The bracketed quantity in Eq. (4), separated into' x- and y-components, is now recognized as the complex amplitude vector E0 for the polarized wave. Note that the far-field angular radius (i.e., the angular half-width) of the Airy disc, according to Eq. (20), is very nearly ¢u1>2 = 1.22l D (21) In Example 3, the beam spread from a circular aperture is compared with that from a single slit. 1 ENERGY QUANTIZATION IN LIGHT AND MATTER Electromagnetic fields result when charged particles are accelerated. 6 Determine the half-wave voltage for a longitudinal Pockels cell made of ADP (ammonium dihydrogen phosphate) at l = 546 nm. Since 4 pixels are used to record the color information, the irradiance is recorded with higher resolution than is the color of the image. In the more general case of complete reflection with an arbitrary phase shift, the positions of the nodes will be shifted from the case depicted in Figure 5b but the nodes will still be separated by l>2. The slit allows only the modulated zero-order beam to be transmitted. A typical reaction might be Kr... + F2 : 1Kr+ F-2... + F The production of the excited rare-gas species is accomplished by electricdischarge or e-beam pumping. Gerard, A., and J. Equation (20) represents a traveling wave moving along the + x-direction. Interference of Mutually BIncoherent Fields B In practice, for electric fields E1 and E2 originating from different sources, the time average in Eq. (13) is zero. The laser linewidth ¢nL is the full width at half maximum (FWHM) of the spectral irradiance associated with the radiation. Recognizing the significance of what he had witnessed, Fyodorov replicated, under controlled conditions, what nature and a fist had accomplished so haphazardly. 13 One eye of a person has a far point of 50 cm and a near point of 15 cm. It does not affect the validity of results like Eq. (8), for example, because measurements depend on the net motion of the fringe pattern, not on precisely where it is dark and where it is bright. That is, Ċ-15Ċ-1f1x226 = Ċ-15g1k26 = f1x2 (5) in accordance with Eqs. Find the pump irradiance Ip required to sustain a steadystate population inversion. Note that the image position does not depend on the position of the eye. b indices of various parts of the schematic eye, as well as radii of curvature of surfaces, may not agree with values of the biological eye itself. 9 Show that if the irradiance throughout a gain cell described by Eq. (41) is much greater than the saturation irradiance IS , the output irradiance IL is related to the input irradiance I0 by the simple relation IL = I0 + ISg0L That is, show that for a very large input irradiance, the irradiance exhibits linear growth. If the curved grating surface is tangent at its center to the Rowland circle, which has a diameter equal to the radius of curvature of the concave grating, then a slit source placed anywhere on the circle gives well-focused spectral lines that also fall on the circle. In this chapter we discuss chiefly the Michelson and the FabryPerot interferometers and suggest only a few of their many applications. (This virtual image is shown as L2œ in the final drawing.) So, for image L2œ : uL2œ M 9>30 = 0.3 rad Comparing half-angles, element A subtends the smallest half-angle and so serves as the aperture stop AS. (a) A typical standing wave situation occurs when a wave E1 and its reflection E2 exist along the same medium. O Tank n 牽 4/3 5 cm 30 cm n 1.50 Figure 34 Problem 10 11 A concave mirror forms an image on a screen twice as large as the object. (b) Construction used to relate distances q, s, and f2 to matrix elements. = ng sin ao = no sin aoœ The maximum value of the numerical aperture when air is used is unity, but when object space is filled with a fluid of index n, the maximum numerical aperture may be increased up to the value of n. What actual material could be used? After re-collecting constants, we get n = A + C B + 4 + Á 2 l l This is the Cauchy relation introduced earlier to describe normal dispersion. Still, the advantages of the diode laser design make them the preferred choice in an ever-increasing array of devices, including laser pointers, optical pumps, and optical data storage and read-out. Assume that the lens diameter D is related to the focused beam waist w0 by the equation D = 4.5 A 22w0 B . (d) When C = 0, a parallel bundle of rays at the input plane is parallel at the output plane and D is the angular magnification. Photons interact directly with the electrons in the detector material. Using P as a center, let an arc S1Q be drawn of radius s1 so that it intersects the line S2P at Q. The argument may, of course, be extended to an observation point at r0>5, when the original zone of radius R1 includes five half-period zones, and the irradiance is 1/25 that at r0 , and so on. Assume that the interferometer is set to a null (no detected power) in the absence of the gravitational strain. These matrix elements are then used in Eq. (36) for the reflection coefficient. That is, if the length of one arm is being reduced, the length of the other arm will be increased due to the passage of the gravitational wave. What is the focal length of the mirror? Verify your results dimensionally. The focal line T lies in the sagittal plane, and the focal line S falls in the tangential plane. Consider Figure 12, which shows the behavior of the gain coefficient during the buildup to steady state in such a medium. Correction for presbyopia is similar to that for hyperopia in that a converging lens is needed to form clear images of nearby objects on the retina. Verdeyen, Laser Electronics, 3d ed. Scanning and readout is performed by charge transfer along each pixel row of such a device. Determine the minimum angle of deviation for sodium light of 589.3 nm. This method of cooling is sometimes used in carbon dioxide and dye lasers. 384 Chapter 16 Holography recording. As soon as the ᶜ mode arrives, however, the two modes superpose to fix the direction of vibration at an angle b in a linear mode. To emphasize this requirement, we write z0 = ƒ z0I ƒ and q1z2 = z - iz0 (14) 1 A more detailed derivation is given in Anthony E. (b) Rhombohedron of calcite, showing the optic axis, which passes symmetrically through a blunt corner where the three face angles equal 102°. Thus positive and negative transparencies of the same pattern produce the same diffraction pattern. (2) and (3), where the timedependent term in the exponent is negative. The variation of refractive index and light speed with wavelength is called dispersion and is discussed later. For this m 20 Lamp Filter Slits m0 0.1 mm Screen 1m Figure 18 18 A Michelson interferometer forms fringes with cadmium red light of 643.847 nm and linewidth of 0.0013 nm. 21 Equation (19) allows calculation of bandwidth for distances less than the equilibrium length of fiber (see footnote 10). In this case, the design aims to minimize the angular spread of the diffracted light; when used as a spectrum analyzer, the design aims instead to maximize it. Tuning the cavity is accomplished by varying the refractive index of the cavity through control of temperature or an applied DC field. The notion of a group velocity is sensible only so long as the pulses "hold together" as the constituent harmonic waves propagate. Although the calculations can be tedious, they are easily done using a programmable calculator or computer. This type of coherence is important when using a wavefront-splitting device, such as the double slit. Whether the errors of refraction occur singly or in some combination (as they often do), they are generally correctable with appropriately shaped external optics (eyeglasses or contact lenses). 22. Thus the z and y values for the center of the spiral length ¢y become increasingly negative. 10 VERGENCE AND REFRACTIVE POWER Another way of interpreting the thin-lens equation is useful in certain applications, including optometry. While achievable, this is a very large irradiance. In most cameras, the aperture is variable and is coordinated with the exposure time (shutter speed) to determine the total exposure of the film to light from the scene. Special cases of electromagnetic waves with elliptical polarization include linearly polarized waves in which the electric field vector always oscillates back and forth along a given direction in space and circularly polarized waves in which, over time, the tip of the electric field vector traces out a circle. We desire solutions to the wave equation, Eq. (3), 584 Chapter 27 Characteristics of Laser Beams 1 irradiance e2 profile lines Figure 1 An external laser beam, confined essentially to regions within the 1>e2-irradiance guidelines, is focused by a converging lens. If the two holes are equal in size, light waves emanating from the holes have comparable amplitudes, and the irradiance at any point of superposition is given by Eq. (18). In general, however, responsivity is not independent of wavelength. This width in the allowed energy levels in turn relaxes the restriction that a photon must have a precise energy that just matches the difference in discrete allowed energy levels. Referring to Figure 22, these are E1 = 1rE02eivt E2 = 1tt¿r¿E02ei1vt - d2 E3 = 1tt¿r¿ 3E02ei1vt - 2d2 E4 = 1tt¿r¿ 5E02ei1vt - 3d2 and so on. If the optical path difference between the two paths is 0.400 mm, calculate the magnitude of the normalized correlation function and the visibility of the resulting fringes. Cotter, The Elements of Nonlinear Optics (New York: Cambridge University Press, 1990), Ch. 6. 530 Signal A3 A4 PC output Chapter 24 A1 Pump beam Nonlinear medium A2 Pump beam A4 A1 A2 A3 Figure 15 Conventional geometry for phase conjugation by four-wave mixing. The nature of these wavefronts that we are about to investigate is illustrated in Figures 2 and 3. Before pursuing Fresnel's quantitative treatment of such cases, consider qualitatively what we might expect by using again the concept of Fresnel half-period zones. From the power conservation requirement, as expressed by Eq. (47), show that for an external reflection the transmission coefficient t must be less than 1, but for an internal reflection t¿ may be greater than 1. By the resolution of a grating, we mean its ability to produce distinct peaks for closely spaced wavelengths in a particular order. If the lens is the objective of a microscope, as indicated in Figure 11, the problem of resolving nearby objects is basically the same. The beams interfere at a point P where the phase difference due to path is p>3 (the first beam having the longer path). The product of the sine and cosine factors may be considered a modulation of the interference fringe pattern by a single-slit diffraction envelope, as shown in Figure 14b. Rayleigh scattering explains why a clean atmosphere appears blue: Higher-frequency blue light from the sun is scattered by the atmosphere down to the earth more so than is the lower-frequency red light. Examination of Figures 4 and 5 shows that, for the case of internal reflection, both RTE = r2TE and RTM = r2TM reach values of unity before the angle of incidence u reaches 90°. 202 Chapter 8 Optical Interferometry We choose not to include electric field changes caused by reflection from or transmission through mirrors in the definition of the propagation factor, but rather we will include these factors explicitly when we track changes to an electric field that encounters mirrors. He suggested, in fact, that a particle with momentum p had an associated wavelength of l = h p (2) where h was, again, Planck's constant. Determine the radius of their Petzval surface. The last defect, astigmatism, is due to unequal or asymmetric curvatures in the corneal surface, thereby rendering impossible the simultaneous focusing, for example, of all the spokes in a manyspoked wheel. Note that the Huygens eyepiece cannot be used as an ordinary magnifier. What aperture diameters correspond to these f-numbers? 7 Research and describe the manner in which a nematic liquid crystal placed between transparent glass sheets with parallel scratches can be used as a voltage-controlled phase modulator. The energy density, uE in J>m3, associated with the electric field in free space is uE = 1 e E2 2 0 (32) and the energy density associated with the magnetic field in free space is uB = 1 1 2 B 2 m0 (33) These expressions, easily derived for the static electric field of an ideal capacitor and the static magnetic field of an ideal solenoid, are generally valid. Example 1 An optical system (see sketch in Figure 4 below) is made up of a positive thin lens L1 of diameter 6 cm and focal length f1 = 6 cm, a negative thin lens L2 of diameter 6 cm and focal length f2 = - 10 cm, and an aperture A of diameter 3 cm. Instead, Eq. (36) can be used to calibrate the length change of the cavity in 207 Optical Interferometry 1 dfsr l/2 0.9 0.8 Transmittance 0.7 0.6 0.5 0.4 0.3 2d1/2 0.2 0.1 0 0 0.05 0.1 0.15 0.2 0.25 Change in cavity length (mm) 0.3 0.35 0.4 (a) Spherical mirrors d Focusing lens Piezoelectric Aperture spacer Driving voltage source Figure 11 (a) Transmittance T as a function of the change in cavity length ¢d, for a monochromatic input field. Then at the instant Ex has reached its maximum displacement— + A, for example—Ey is zero. If the maximum diameter of the circle of confusion is taken to be 0.05 mm, determine the depth of field of the photograph. One rarely finds a He-Ne laser shorter than 15 cm. 4 A TEM00 He-Ne laser 1l = 632.8 nm2 has a beam waist w0 (at z = 0) of 0.5 mm and a beam divergence of uFF = 0.4 mrad. The concern that CFCs and other similar chemicals may contribute to the depletion of the ozone layer and thus increase the risk of skin cancer led to protocols calling for the reduction of the use of refrigerants, aerosol sprays, and other products that release these chemicals into the atmosphere. (b) Twyman-Green interferometer used in the testing of a prism and a lens (inset). The variation of um with l is described by the grating Eq. (2), from which we may conclude Ↄ = m a cos um (5) If a photographic plate is used in the focal plane of the lens to record the spectrum as in Figure 2a, it is convenient to describe the spread of wavelengths on the plate in terms of a linear dispersion, dy>dl, where y is measured along the plate. This property is precisely described by the angular dispersion, Ↄ, defined by Ↄ K dum dl (4) which gives the angular separation per unit range of wavelength. we have, r = r0 c 1 - 1xX + yY2 r20 d (12) In Eq. (9), the factor r appears in both the amplitude and the phase. Finally we describe several current surgical procedures that can restore visual acuity in less-thanperfect eyes. The short-term stability of commercially available CO2 lasers, for example, is such that line widths of around 1 * 10-5 nm are attainable at the infrared emission wavelength of 10.6 mm. Using Eq. (12) with m = ; 1 and approximating sin u by u, we get ¢u = 2l b (14) From Eq. (14), it follows that the central maximum will spread as the slit width is narrowed. The distance between the fifth minima on either side of the zeroth-order maximum is measured to be 34.73 mm. If the stars are near the center of our galaxy, a distance, d, of around 30,000 light-years, then their actual separation s is approximately s = d ¢umin = 130,000211.92 * 10-52 = 0.58 light-years To get some appreciation for this distance, consider that the planet Pluto at the edge of our solar system is only about 5.5 light-hours distant. 3 a. Real, nonlocalized fringes appear as in the two-point source pattern of Figure 6. Two images are formed in reconstruction. Gratings with more slits produce brighter and narrower principal maxima. These missing orders are expected when the slit separation is twice the width of the slit opening, precisely the case in the Ronchi ruling. Making use of the defining equation for radiance Le in Table 1, we ob¢Ie , where we have replaced the differentials dIe and tain Le = ¢A S cos u £ dAs by the small quantities ¢Ie and ¢A s. The sine and cosine terms can be interpreted as harmonic waves with amplitudes of bm and am , respectively, and frequencies of mv. Furthermore, they produce higher-order images of the same wavelength component, which can be confusing when interpreting spectral records. When half-wave voltage is applied to the Pockels cell, it rotates the linear polarization of the laser beam so that it can be dumped by the polarizing prism. 2 80 (1) See, for example, Christopher C. Various stages in solving the lens design problem are illustrated in Figure 23a, from the single-element meniscus lens, which may still be found in simple cameras, to the four-element Tessar lens. 14 A thin, plano-convex lens with 1-m focal length and index 1.60 is to be used in an orientation that produces less spherical aberration while focusing a collimated light beam. This process is known as gain saturation. An inelastic process leading to scattered light at frequencies different from the incident light is known as spontaneous Raman scattering. Note that the wavefronts associated with adjacent maxima are separated by one wavelength. The design of a multilayer stack that will meet arbitrary prespecified characteristics, however, remains a formidable task. Example 4 Consider a homogeneously broadened transition in a carbon dioxide 1CO22 laser. We wish to determine the image distance x and the lateral magnification m. Neighboring dark fringes decrease in order outwards from the center of the pattern, as cos u decreases from its maximum value of 1. For a fixed ratio of 1sin um2>l, however, the grating equation also fixes the ratio m/a. At a given place in the cavity, the condition for a common phase for all of the fields recurs at times equal to the inverse of the constant frequency separation of the modes. On the other hand, for object points along radial lines in the object circle, sharp radial images are produced only in the S surface, where the elongated radial images merge to produce well-focused radial lines. Long-wavelength waves, traveling deep in the ocean, have a speed given approximately by yp = a gl 1>2 b 2p 130 Chapter 5 Superposition of Waves where g is the acceleration of gravity. The thin-lens equation, in terms of the focal length, is then 1 1 1 = + s s¿ f (29) Wavefront analysis for plane wavefronts, as shown in Figure 21, indicates that a lens thicker in the middle causes convergence, and one thinner in the middle causes divergence of the incident parallel rays. In addition, the use of Porro or other prisms to produce erect final images also permits the distance between objective lenses to be greater than the interpupillary distance, enhancing the stereoscopic effect produced by ordinary binocular vision. For the example of glass 1n = 1>1.52 used in Figure 5, upœ = 33.7° and uc = 41.8°. These atoms bond in the solid lattice in such a way that each atom sees a full outer shell (eight electrons) with some of these electrons shared with neighboring atoms. Subsequent principal maxima are less bright since they are limited by the diffraction envelope, sin2 b>b 2 (dashed line). Solution The reflection and transmission coefficients for this situation are given in the solution to Example 1. Example 5 Estimate the linewidth of an Ar+ gain medium. Light from the text to be searched is passed through a hologram of the letter or word to be identified in an appropriate optical system. 6 (a) express the relation in terms of n and v and (b) determine whether the group velocity is greater or less than the phase velocity in a medium having a normal dispersion. For this reason, temporal coherence is also called longitudinal coherence. The depth of field, MN = s2 - s1 , can be expressed as depth of field = 2Ads01s0 - f2f2 f4 - A2d2s20 (32) Acceptable values of the circle diameter d depend on the quality of the photograph desired. For the case of a plane refracting surface, Eq. (21) may 34 Chapter 2 Geometrical Optics n1 n2 ho u1 C I V O hi u2 Figure 19 Construction to determine lateral magnification at a spherical refracting surface. 7 The rate of decay of an assembly of atoms with population density N2 at excited energy level E2 when spontaneous emission is the only important process is a dN2 b = - A21N2 dt spont Show that an initial population density N20 decreases to a value N20>e in a time t equal to 1>A21 . Since the state of polarization of the light is completely determined by the 1 R. In this case, I = 4I0 cos2[p10.00022y>1658 * 10-9211m2] = 4I0 cos2[1955>m2y] An alternative way to view the formation of bright (B) positions of constructive interference and dark (D) positions of destructive interference is shown in Figure 5. Matrix Methods in Paraxial Optics 411 If input and output reference planes are located at the lenses, the system matrix includes two thin-lens matrices, ᶜA and ᶜB , and a translation matrix Ᵽ for the distance L between them. Using the expression given earlier, Ep = Pp ¢tp = 14 * 104 W210.25 * 10-6 s2 = 0.01 J = 10 mJ P T Pp ©tp t Figure 14 Construction showing a rectangular pulse approximation to Q-switched pulses used in Example 6. The conditions are frequency dependent. Example 3 A Fabry-Perot interferometer has a 1-cm spacing between mirrors and a reflection coefficient of r = 0.95. So, 1 1 1 L = + feq fA fB fAfB (32) Furthermore, the first principal points and nodal points coincide at a distance given by r = y = 1D - 12>C from the first lens, and the second principal points and nodal points coincide at a distance given by s = w = 11 - A2>C from the second lens. ym mlL a ym S 3 DOUBLE-SLIT INTERFERENCE WITH VIRTUAL SOURCES Interference fringes may sometimes appear in arrangements when only one light source is present. Two calcite prisms with apex angle u, as shown, are combined with their long faces opposed and separated by an air space. This radiation is believed to have originated early in the development of the universe, when the universe was hot and dense. If the object in the aperture plane is shifted by an arbitrary translation given by components 1qx , qy2, for instance, its transmission function must reflect a translation of origin within the xy-plane, and Eq. (26) is expressed more generally by q Ċ[E11- x, - y2E21x, y2]DC = O E11qx - x, qy - y2E21x, y2 dx dy -q (27) The integral in Eq. (27) is an example of the two-dimensional convolution function, q r121qx , qy2 = O -q f11qx - x, qy - y2f21x, y2 dx dy (28) 468 Chapter 21 Fourier Optics If the transmission function possesses inversion symmetry, that is, if f11- x, - y2 = f11x, y2 then the negative signs in the integrand of Eq. (28) may be written as positive signs, and the integral is instead the correlation function, £ 121qx , qy2 = Ċ[f11x, y2f21x, y2]DC (29) q £ 121qx , qy2 = O f11x + qx , y + qy2f21x, y2 dx dy -q Further, when f1 and f2 are merely shifted versions of the same function, we speak instead of the autocorrelation function, q £ 111qx , qy2 = O -q f1x + qx , y + qy2f1x, y2 dx dy (30) Transmission functions with inversion symmetry are imaged in such a way that the actual image inversion due to the lens is not apparent. Thus, /t = l2>¢l = 15410 A V = 1 - 1.5 = 0.49 2.93 When the path difference is doubled, ¢ 7 /t and t 7 t0 , so that the beams are incoherent and V = 0. Before wavelengths of spectral lines appearing in a region of overlap can be assigned, the actual order of the line must first be ascertained so that the appropriate value of m can be used in Eq. (2). No interaction at all would make y = c. Peter Franken and his associates are credited with the first nonlinear coherent optics experiment,3 conducted at the University of Michigan in 1961. 526 Chapter 24 Nonlinear Optics and the Modulation of Light application of the Faraday rotator as an optical isolator. n2 ⬘ w c l1 n1 ⬘ ⬘ wc l1 B A ⬘ wc ⬘ L 10 Fiber Optics INTRODUCTION The channeling of light through a transparent conduit has taken on great importance in recent times. The photoresist is spread evenly over the surface of the glass blank to a thickness of 1 mm or less by rapidly spinning the blank. Solution The atomic mass of an argon atom is M = 6.64 * 10-26 kg. In this context it is important to distinguish between specular reflection from a perfectly smooth surface and diffuse reflection from a granular or rough surface. As a consequence, only the first-order diffraction, m = 1, occurs in the acousto-optic effect. To deal with cylindrical lenses and astigmatism in a general way, then, we must be able to determine the effect of combining cylindrical lenses having arbitrary orientations with each other and with spherical lenses. The incident E-vibration is shown resolved into orthogonal components (aa) parallel to the OA and (bb) perpendicular to the OA. Notice that the first term for spherical aberration agrees with Eq. (19), derived for axial imaging, where h represents the aperture. Solution The grating constant or groove separation a is a = 1 = 2 * 10-4 cm 5000 cm-1 Clearly, for zeroth order, there is no dispersion. Determine the Rayleigh range z0 for the Gaussian beam generated by this cavity. In dispersive media, however, yp = c>n, where the refractive index n is a function of l or k. According to the usual criterion, which technique (near-field or far-field) may be applied to the diffraction problem when the detector is at 50 cm, 1 m, and 5 m from the aperture? The values of the parameters M and M¿ are 43 ps/nm-km and 3 ps/nm-km, respectively. Example 2 A ring laser cavity system like the one shown in Figure 8 uses mirrors with reflectances R1 = R2 = 0.99 and R3 = 0.95. Find the diameters of the first three clear zones such that the plate focuses parallel light of wavelength 550 nm at 25 cm from the plate. If three sources of light of equal radiant power but radiating blue, yellow, and red light, respectively, are observed visually, the yellow source will appear to be far brighter than the others. (See problems 24 and 25.) Note that, as shown in Figure 13, in the approach to steady state a laser system can produce pulses of intracavity photon number densities Np that far exceed the steady-state photon number density. 3 The ratio of the amplitudes of two beams forming an interference fringe pattern is 2/1. If all 100 W is emitted from a red bulb at l = 650 nm, calculate also the illuminance at the surface. 182 Chapter 7 Interference of Light fringes by reflected light. The myopia itself causes an overall blurring of distant objects; the astigmatism compounds the problem by adding considerably more blurring in one meridian than another. The diffraction pattern due to this grating may be quite complicated, but the raster lines, like a Ronchi ruling, produce a series of diffraction spots along the vertical direction in the spectrum plane. 25 Geometrical Optics The image point occurs at the vertical distance s¿ below the surface given by s¿ = a n2 bs n1 (4) where s is the corresponding depth of the object. Spectral lines formed in this way may suffer rather severely from astigmatism. Figure 10b shows a plane wave propagating along the positive z-direction with the electric field varying along the x-direction and the magnetic field varying along the y-direction. Siegmund, "Fiber Optics," in Handbook of Optics, edited by Walter G. A photograph that freezes motion of the specimen captures in a focused image a very limited depth of field within the specimen. Find (a) the equivalent focal length and (b) the magnifying power for an image formed at the near point of the eye. Situated in the aqueous humor is the iris, a diaphragm that gives the eye its characteristic color and controls the amount of light that enters. This spontaneous emission process is responsible for the output of light-emitting diodes and is illustrated in Figure 18a. (36) and (37), is 2nft + ¢ r = e ml, A m + 12 B l, bright dark (38) where ¢ r is either l>2 or 0, depending on whether there is or is not a relative phase shift of p between the rays reflected from the top and bottom surfaces of the film. (From M. Thus, as the pinhole is reduced in size, the image improves in clarity, until a certain pinhole size is reached. When h is taken as the maximum extent of the aperture in either direction or as the radius of a circular aperture, Eq. (9) or Eq. (10) may also be expressed approximately by the condition near field: d 6 A l (12) where d represents either p or q and A is the area of the aperture. The green line of mercury at 546.07, which lies nearer to the center of the luminosity curve, is also used. Such fibers are called step-index fibers because the refractive index changes discontinuously between core and cladding. What wavelength is minimally reflected when the light is incident instead at 45°? This inexpensive method for artificially flattening the field has been used in simple box cameras. Siegman, Lasers (Mill Valley, Calif.: University Science Books, 1986), Ch. 16. Once the virtual image separation a is related to the tilt angle u and to the distance d from actual source to the intersection of the mirrors at O, the fringe pattern may again be described by Eq. (22). (Handbook data for copper: s = 5.76 * 107>Æ-m.) 7 Compare the skin depth of (a) aluminum, with conductivity of 3.54 * 107>Æ-m and (b) seawater, with conductivity of 4.3> Æ-m, for radio waves of 60 kHz. 8 Calculate the skin depth of a solid silver waveguide component for 10-cm microwaves. Thus, the spatial coherence of light at Double slit A B S P1 Michelson interferometer P2 Figure 11 Wavefront and amplitude division of radiation from source S, illustrating the practical requirements of spatial and temporal coherence. Figure 2 Golay pneumatic infrared detector. For a sound wave having a width of 1 cm, calculate the advance of the sound wave while it is traversed by a light wave. 23 Consider the transmittance through a Fabry-Perot interferometer as a function of the variable wavelength l of its input field. Sample ray diagrams for converging (or convex) and diverging (or concave) lenses are shown in Figure 22. The ruled width of the grating is to be 2 cm. Leaving the lens fixed, the object is moved to a new position and the image screen moved until it again receives a focused image. Here the coordinate y could, for example, represent the transverse displacement from equilibrium of a string stretched out along the x-direction. The proper expression for kinetic energy is no longer simply EK = 12 my2, but rather is EK = mc21g - 12, where g = 1> 21 - 1y2>c22. The word laser is an acronym that stands for light amplification by the stimulated emission of radiation. As you follow through the steps in the solution, be sure to verify the correct use of the sign convention related to the object distance s, image distance s_i, focal length f, and image magnification m = - s_i/s for each calculation. 216 Chapter 8 Optical Interferometry Example 5 A certain argon-ion laser can support steady-state lasing over a range of frequencies of 6 GHz. That is, the gain bandwidth of the argon-ion laser is about 6 GHz. If the length of the laser cavity is 1 = 1 m, estimate the number of longitudinal cavity modes that might be present in the laser output. A more precise statement of Fermat's principle, which requires merely an extremum relative to neighboring paths, may be given as follows: The actual path taken by a light ray in its propagation between two given points in an optical system is such as to make its optical path equal, in the first approximation, to other paths closely adjacent to the actual one. We take the half-width of the central maximum, or 2p>l0 , to indicate in a rough way the range of dominant frequencies required. 9 A zone plate is to be produced having a focal length of 2 m for a He-Ne laser of wavelength 632.8 nm. Such a system must meet several stringent design considerations. The corresponding composite phasors A n are shown in Figure 5b. As a result, the electronic oscillators reemit radiation in all diB rections. The high-current arc is formed between two carbon rods in air. Incident, reflected, and refracted rays are shown in the plane of incidence. 144 Chapter 6 Properties of Lasers light is shown in Figure 12b. The converging lens reshapes the wavefronts and focuses the beam—forming a beam waist—to the right of the lens. The refracted ray locates an axial image at I. The two basic types of holograms discussed in the preceding paragraph are the Gabor zone plate and holographic grating, corresponding to point objects at a finite distance and at an infinite distance from the plate, respectively. The E-vibration in light reflected from a horizontal surface into the eye is preferentially polarized along the horizontal direction. A signal cannot be extracted from noise unless the mean signal Optical Detectors and Displays photon number n exceeds the uncertainty in photon number 2n. Analyzer The rotator mechanism involved in rotating the direction of vibration of linearly polarized light is distinct from the action of phase retarders, such as half-wave plates discussed in Section 4, which may produce the same result. On returning to the beam splitter, beam 2 is once again transmitted and beam 3 is reflected by the semitransparent film so that they come together again to form a screen, where the interference may be observed. Determine the irradiance at (a) 1 mm outside the edge of the geometrical shadow. These electrons are said to be in the conduction band of electron energy states in the solid. The resulting convergent beam is shown in Figure 1b. In that case, light of free-space wavelength l1 will constructively interfere in the direction of Output 1 if the difference in path lengths of Path 1 and Path 2, εL, is given by εL = ml1>n m = 0, ; 1, ; 2 A (21) Under this condition, light of wavelength l1 will not be present in Output 2. This arrangement is used because the eye is more sensitive to green light than to either red or blue light and doubling the information obtained in the green portion of the spectrum allows for the production of an image that the eye perceives as "true" color. 15 Determine (a) the length and (b) transit time for the longest and shortest trajectories in a step-index fiber of length 1 km having a core index of 1.46 and a cladding index of 1.45. Such polarized light patterns for a beam under light and heavy stress is shown in Figure 21. on the screen. The resulting air layer between the slides shows Fizeau fringes when the slides are illuminated by monochromatic light. Solution According to Eq. (18), with object distance s very large, there remains a = -h4 n2 1 1 2 c a - b d8 s¿ s¿ R To calculate by and then by , one needs the derivative dadhb. h3 n2 1 2 -h4 a - = -a b - a b dh 2 s¿ s¿ R The maximum value of dadh, therefore, occurs when h has its maximum value of 4 cm, or dadh = 2 a 1 2 s¿ 2 a 0.04 - 1 0.6 3.5 b = -0.001 so that a = - 0.0017 and b = a a 10.667 cm Then dadh and the spherical aberrations are, a 1 1.6 1 1 2 = - c a - b d = - 0.00183 1 2h 1 0.667 10.667 4 by = s¿ da 10.667 s¿ da = = 1 -0.001831 2 - 0.0122 cm n2 dy n2 dh 1.6 br = s¿ s¿ 10.667 1 - 0.01222 = - 0.130 cm by = br + h 1 Figure 6b shows spherical aberration when the object is at infinity. In addition, solids and liquids can have energy levels associated not with individual atoms and molecules, but with the entire solid. The broadened image there is called, descriptively, the "circle of least confusion." Using Eqs. Of course, any obstruction placed inside the telescope reduces the cross section of the incident light waves contributing to the image. 552 Chapter 24 Laser Operation Population densities should be zero. Pulse distortion limits transmission frequency and information rate in a way that we can roughly estimate. 2 YOUNG'S DOUBLE-SLIT EXPERIMENT The decisive experiment performed by Thomas Young in 1802 is shown schematically in Figure 3. Calculate the minimum resolvable wavelength difference in the second order. The multiplied current is collected at the anode. As a result, free electrons can interact with photons of any frequency. In dealing with crystalline media, which represent most of the useful electrooptic materials, it is customary to express nonlinearity of the refractive index n by an equation5 analogous to Eq. (2) for the susceptibility: 1 1 = 2 + rE + RE 2 2 n n0 (7) where r and R are the linear and quadratic electro-optic coefficients 6 respectively, and we assume that there is no other effect present (the linear electro-optic effect, also known as the Pockels effect, and the quadratic effect, the Kerr effect). When an arbitrary polarization direction represents some linear combination of these two special cases. Important and interesting features of this relationship are illustrated in the problems at the end of this chapter. The Resonator Given a suitable pump and a laser medium that can be inverted, the third basic element is a resonator, an optical "feedback device" that directs photons back and forth through the laser (amplifying) medium. (a) Refraction of monochromatic light. Since materials with nonzero second-order susceptibilities x2 lack inversion symmetry, the resulting crystal will have a second-order susceptibility that changes sign each coherence length of the crystal, as shown in Figure 2b. Changes in elevation of the horizontal lines suggest the magnification in the various regions. The light is assumed to be emerging from the page. Thus it is in the local variations of fringe contrast and spacing across the hologram that the crystal spreading variations in amplitude and phase of the object waves are encoded. The mathematical treatment, however, is more complex and is almost always handled by approximation techniques, as we will see. 8 Derive the Wien displacement law from the Planck blackbody spectral radiance formula. When both dimensions of 1 A laser beam usually does not have constant irradiance across its diameter. Thus, from Eq. (12), we conclude that g1v2 = v : v0 0 2p (13) Furthermore, the sinc function (sin u)/u vanishes whenever sin u = 0, except at u = 0, the case already described by Eq. (13). At each of the minima, the phasor diagram forms a closed figure, so that cancellation is complete. The center frequency of the transition is n0 = Eh - Em>h. Blackbodies are approached in practice by blackened surfaces and by tiny apertures in radiating cavities. If some birefringent material is inserted between them, light is generally transmitted in beautiful colors. In many cases, the precise phase of the wave is not of interest. The solutions to this problem are illustrated in Figure 13b and c. These waves exert forces on charged particles in the surface of the metal, and the charges move in response. 256 Chapter 10 Fiber Optics The variation of refractive index with fiber radius is given,7 in general, by n1r2 = n1 rap 1 - 2a b c a , B 0 ... r ... a (15) where є 1n1 - n22>n1 and n1 = [n1r2]max . As the observation point P- moves from P to lower points on the screen, the temperature dependence phase endpoint B slides along the Cornu spiral away from O, with its other end fixed at E. This term is important primarily in gas media. Englewood Cliffs, NJ: Prentice-Hall, 1976. The fraction of light removed from the zero-order diffracted beam depends on the amplitude of the ultrasonic wave and so on the amplitude of the modulating RF signal. Even if individual spiral-shaped molecules confront the light in random orientations, as in a liquid, there will be a cumulative effect that does not cancel, so long as all of the molecules are of the same handedness. 5 Refer back to the extended example in the text, involving both a positive and a negative lens, of focal lengths 6 cm and - 10 cm, respectively. Most often, as in the case of the thick-lens example, n0 and of both refer to air, and Det (M) is unity. Adaptation The ability of the eye to respond to light signals that range from very dim to very bright, a range of light irradiances that differ by an astonishing factor of about 105, is referred to as adaptation. This simple and versatile instrument was used, for example, to establish experimental evidence for the validity of the special theory of relativity, to detect and measure hyperfine structure in line spectra, to measure the refractive index of gases, and to evaluate the meter in terms of wavelengths of light. Example 1 The cross section r, for a transition from the ground state to an excited state that is resonant with an electromagnetic field of wavelength 808 nm, for a neodymium (Nd) atom doped into a YaG (yttrium aluminum garnet) crystal4 is about 3 * 10-20 cm2. Light from a monochromatic (temporally coherent) point source (spatially coherent) is collimated by lens L1 and illuminates, in the input or aperture plane, a two-dimensional pattern whose transmittance varies across the aperture. Wavelengths of microwaves range roughly from 1 mm to 1 m. approached as it becomes perpendicular to the incident light. Elliptically polarized light traveling in the x,y-plane in a direction making an angle of 45° relative to the x-axes. Twyer, Atlas of Optical Phenomenon, Plate 36. Berlin: Springer-Verlag, 1962.) (41) with A and B representing any two complementary apertures. Figure 13 illustrates one means of achieving AM modulation using Nonlinear Optics and the Modulation of Light 529 First-order diffraction u1 Incident light beam Zero order Modulated beam Figure 13 Modulation of a light beam by an acousto-optic grating in the Raman-Nath regime. Regular astigmatism can be corrected with a lens that has cylindrical surfaces ground on the back surface of the required spectacle lens. (b) Wavefronts for a (linearly polarized) plane electromagnetic wave. In Figure 3c, the locations of the stops, pupils, and windows are shown in a more complex optical system consisting of two lenses and two apertures. Of course, there are also cubic crystals such as salt (NaCl) or diamond (C) that are optically isotropic and possess one index of refraction. Letting P represent a refraction matrix and P represent a translation matrix, the matrix for the thick lens is, by Eq. (14), the composite matrix M = P2PP1 or M = C nL - n¿ n¿R2 0 nL S C 0 n¿ 1 S C 1 - nL 1 nLR1 0 n S nL (15) The lens is a thin lens if the surrounding medium is the same on both sides. Since R1 = 2 n = n¿ n 1 - A B + A B C c r , A B R2 1 0 nL S C 0 n 1 S C 1 - L nLR1 0 n S nL (16) Simplifying Eq. (16), 1 M = C nL - n L 1 - 1 b n R2 R1 0 1 S (17) The matrix element in the first column, second row, may be expressed in terms of the focal length of the lens, by the lensmaker's formula, nL - n 1 1 1 b a - = n f R1 R2 so that the thin-lens ray transfer matrix is simply 1 M = C - 1 f 0 1 S (18) Progress of a ray through a thick 404 Chapter 18 Matrix Methods in Paraxial Optics As usual, f is taken as positive for a convex lens and negative for a concave lens. Accordingly, a section of a sine wave is pictured in Figure 2. Thus we define the phase difference, according to Eq. (32) as ¢ = IPQI - POI2ped (5) where ped is the optical-path difference. Conservation of momentum in a collision between a phonon and a photon requires. 8 This sign convention is the same as that used in chapter 2. Figure 8 shows the transmittance spectrum for a typical edge filter. The Transverse Electric Field: TE ray, see Section 20, where the ref n1AB + BC2 - n0AD2 where n0 and n0 are the refractive indices of the film and external medium, as shown. Notice that this nonoverlapping spectral region is smaller for higher orders. One wavelength is known to be 436 nm. Such a plot, for several choices of r, is given in Figure 9. 2 The critical angle for a certain glass is found to be 33°33¿. As an example, Figure 8, we have chosen as a function the top half of a circle. 5 THE REFLECTION MATRIX Finally, consider reflection at a spherical surface, illustrated in Figure 7. Ozone (O3) is formed when UV-C radiation reacts with oxygen in the stratosphere and, as mentioned, plays an important role in the filtering of UV-B and UV-C from the electromagnetic radiation that reaches the earth's surface. 490 Chapter 23 Fresnel Equations TE 90 80 70 R (%) 60 External reflection (air-to-glass) 50 40 30 Internal reflection (glass-to-air) 20 TE 10 TM 10 Figure 4 Reflectance for both external and internal reflection when n1 = 1 and n2 = 1.50. Take the mirror separation to be d and see the mode structure in part (a) of Problem 15. This can be understood by resolving the incident light into equal orthogonal components along the FA and SA (slow axis) and with a p phase difference between them. The negative sign implies a virtual image for a real object. X-ray holograms could provide strikingly detailed three-dimensional images of microscopic objects as small as viruses and DNA molecules. a21/2 R21/2 pw2(z)2 e. In many common applications the source is a laser, in which case the lenses shown in Figure 7b may not be needed. Consider the superposition of two such waves of different frequency and wavelength but with the same speed through the medium: E1 = E0 cos1k1x - vt12 (27) E2 = E0 cos1k2x - vt22 (28) The superposition of these waves, which are traveling together in a given medium, is ER = E1 + E2 = E0[cos1k1x - vt12 + cos1k2x - vt22] Making use of the trigonometric identity, cos a + cos b K2 cos 121a + b2cos 121a - b2 and identifying a = k1x - vt1 b = k2x - vt2 (29) 124 Chapter 5 Superposition of Waves we have ER = 2E0 cos c 1v1 + v22 1k1 - k22 1k1 + k22 x t d cos c x 2 2 2 2 2 (30) Now let us deal with the case of a uniform aperture. (b) Mirror C can be moved along a straight line along the direction shown and a ray of light from a source at O is incident on C. Example 1 Analyzing Eq. (21) for a time interval t of 1 s can be made to create what is called a sine wave in the x direction, here Eq. (18) A second example has been = -11 W211 s2 = 1 J This emitted energy is a small fraction of the photo energy in n = hcl. To record different regions of the spectrum, the grating can be rotated and higher orders can be used. 175 Interference of Light included at a small relative angle u. Optical Correlation As we have seen, an image of the two-dimensional object situated in the aperture plane is formed in the image plane of the optical filter (Figure 5). (Refer to the discussion in Problem 4.) 395 6 Discuss how a twisted nematic liquid crystal between crossed polarizers can be used as a voltage-controlled irradiance modulator. The design of a complex lens system, such as a photographic lens with four or five elements, is a combination of science and art. Using the result that is valid for a linear cavity, one can show (see problem 23) that the cavity loss rate for the positive charge center in the dipole, or E qx q e r p 6d B p e = -grB (1) p approximately. 8 Note that Eq. (55) predicts a zero-growth rate if there are no photons in the cavity. In either case, the B dipole moment p due to each atom or molecule is given by the product of the magnitude of the displaced charge q and the vector B that locates the effective negative charge center relative to the positive charge center in the dipole, or E qx q e r p 6d B p e = -grB (1) p approximately. Unfortunately, this equation is, in general, difficult to solve. Time-division multiplexing is an alternative approach that ensures that all time slots in a stream of bits of information are used to carry information. Even for photographic purposes, as will be seen later in greater detail. Apparently, the single type of visual pigment in rods is much more sensitive to light than is any of the three pigments in cones. As in the example of Figure 20, two refractions at spherical surfaces are involved. The reflection at B, on the other hand, occurs for light going from a higher index of toward a lower index, so refraction occurs. Modern Optics and Systems. (Recall that "small signal" is code for "let I = 0.") c. If means are provided for recording the spectrum, for example, with a photographic film in the focal plane of the telescope objective, the instrument is called a spectrograph. For example, an opaque screen with a round hole represents such an obstruction. The angular separation of the two beams is shown as 2u, and the constructive fringes (vertical dashed lines) formed in the emulsion are labeled as G. Nevertheless, determine the distance above the axis at which single-slit Fraunhofer diffraction predicts the first zero in irradiance. Incorporating Eq. (23), p = -y0 0 = a0 C (24) Similarly, a0 = y0-1 +l2, and thus l1 = l1 = 1 Ay0 + Bqi2 + e0l0 = B - and a0 C Det(M)2 n0 1 AD - BC = n n a a f (25) Finally, the image is a fixed height in the plane. 2 Analyzed by use of 2 × 2 ray matrices, we have = a cos t. This concept of phase-shifted intensity was introduced to the subject of orthography. In Young's experiment the light from a single slit source is stopped and adjusted to stress for analysis. Comparing this matrix with the general form in Eq. (5), we determine that EOx = A = 1 and E0y = 2B2 + C 2 = 1. Shifting the time origin by T1 and defining the difference in the times of flight for the two paths to be t = T1 - T2 , the irradiance at point P can be written as, I = I1P + I2P + e0cb I b 2 ReE1t2E...1t + 1T1 - T2229 = I1P + I2P + e0cb I b 2 ReE1t2E...1t + t229 The remaining time average has the form of a correlation function. For an aperture diameter 4.5w = 2 cm, the collimated beam length becomes 98 m for the He-Ne laser and 5.8 m for the CO2 laser, increasing as the square of the aperture diameter. Equation (20) should be compared with the analogous equation for the narrow rectangular slit, m1 = sin u. This intermediate image, located at or near the focal point of the ocular, serves as a real object (RO) for the ocular in the astronomical telescope and a virtual object (VO) in the case of the Galilean telescope. The initiation of such a pulse can be viewed as the fortuitous spontaneous emission into the different cavity modes in such a way that the fields in these modes happen to constructively interfere at the gate when the gate is open. Even with the narrowest of slit widths, however, the spectral line image is found to possess a width, directly traceable to the limitation that the edges of the collimating lens or prism face impose on the light beam. As a result, the near point of an eye tends to move further from the eye as the eye ages. In step 1 of Figure 15a, energy from an appropriate pump is coupled into the laser medium. Solution The longitudinal cavity modes are separated by the laser cavity, laser eke = 3 # 108 m>s c = 0.15 GHz 2l 2(1 m) Therefore, the number of lasing modes would be given by # of lasing modes L 6 GHz = 40 0.15 GHz To ensure single-mode operation, the free spectral range of the etalon must exceed the gain bandwidth. Modern Optics. Essential distinctions between photons and electrons are removed and both are subject to the same general principles. 1973): 1703. The object and image positions are separated by a distance L that is more than four times the focal length of the lens. This fourth beam, pictured with complex amplitude A in Figure 15, will be the spatial complex conjugate of the signal beam, A S . The chart is to include rows of letters to test for visual acuities of 20/300 (same as 6/75), 20/100, 20/60, 20/20, and 20/15. 111 Wave Equations The Doppler effect is especially important when used to determine the speed of astronomical sources emitting electromagnetic radiation. The light scattered in various directions from the milk molecules, when examined with a polarizing filter, is found to be polarized, as shown in Figure 7. The detail shows how to relate a change da in wave aberration to a change dy in the aperture dimension. If the doublet is to be used in air, determine (a) the system matrix elements for input and output planes adjacent to the lens surfaces, (b) the cardinal points; (c) the focal length of the combination, using the lensmaker's equation for each lens. The arrow shows the direction of light through the compensator. The radiation from real surfaces is always less than that of the blackbody, or Planckian source, and is accounted for quantitatively by the emissivity, є. This condition occurs most frequently when one or the other of the oppositely directed waves experiences a reflection at some point along its path, as in Figure 5a. Third Edition Introduction to Optics FRANK L. m nmax 100 p nmax = 0 Figure 2 Alternate orderings of fringes. Here, "a brief period" means a fraction of a round-trip time. Townes and co-workers developed a microwave amplifier based on stimulated emission of radiation. What minimum thickness is required to produce a quarter-wave path difference for sodium light of 589 nm? (0 R(t) 1 (b) Because the optical fiber is dispersive, we describe the speed of propagation of a pulse by its group velocity, vg. Many radiometric terms have been introduced and used in the optics literature; we include here only those approved International System (SI) units. Again, this requirement places a limitation on the frequency of input pulses or the rate at which bits of information may be sent. 27 The gain bandwidth (in nm) and the transition wavelength for the different laser systems are given below. Looking along the axis into the plane surface, one sees two images of the bubble. The irradiance is plotted as a function of h in Figure 2. That rot is, find Erot 1 - E0 . Let us introduce a wave number or "normalized" form of the spatial frequencies to Transform series by k= kX t 1 = P 2p (22) Then, substituting for kY from Eq. (21) and for Y from Eq. (20), we have, for the spectrum of spatial frequencies displayed in the diffraction pattern, n Y = m = (23) The central spot with m = 0 thus corresponds to a normalized spatial frequency nY = 0, the DC component, in analogy with electrical frequencies. Employing Fermat's principle, the ray FTW is isochronous with ray GX, since they begin and end on the same plane wavefronts, GF and XW, respectively. With the metal wires, the mobile free electrons are set in oscillatory motion by the oscillations of the electric field of the incident radiation. The noise is that part of the signal or output not related to the desired input. Here, S is the survival function in the linear unsaturated gain (35) is 822. TA VBW Linear polarizer Recall that for a half-wave plate the linear polarization of the emergent light is rotated by 90° relative to the linear polarization of the incident light. Thus, a biological 82 Chapter 3 Optical Instrumentation objective compensates for the aberration introduced by a cover glass. 14. That is, z0 is related to the depth of focus of the beam. Use the matrix approach and analyze the final lenses vector to describe the product field. FOURIER-TRANSFORM SPECTROSCOPY Fourier-transform spectroscopy represents an elegant alternative to traditional methods of spectrum analysis. This embraces the hologram onto the mylar, which is then attached to the credit card. (a)1 Path 2 BS2 Input 1 l1, l2 l1, l2 Delay Path 1 Path 1 Input 1 BS1 M2 FC1 l1, l2 Path 2 l1 1 2 (a) (b) l1, l2 Output 2 BS2 Fiber Optics enters the interferometer through the port marked Input 1. In this case, the polarization of the light does not change as it progresses across the cell and so vertically polarized light entering the twisted nematic cell is blocked by the second polarizer, which has a horizontal transmission axis. 10 White light (400 to 700 nm) is used to illuminate a double slit with a spacing of 1.25 mm. The rates of stimulated emission and absorption are equal, and so the "downward" (2 to 1) rate always exceeds the "upward" (1 to 2) rate, thus a steady-state population inversion cannot occur in a two-level atomic system. A circular fringe pattern like the one shown may be photographed at the screen. To see this more clearly, refer to Figure 3, which shows a spherical wave disturbance originating at O and incident upon an aperture with an opening SS¿. The photons scattered in the spontaneous Raman process can act as seed photons, which in turn stimulate additional Raman scattering processes. Assuming that the laser beam has cross sectional area a A = 0.1 cm2, find the output power of the laser. Note that one of the elements of the Jones vector in Eq. (9) is now a complex number having both real and imaginary parts. In that event there is a steady increase in the incident resonant photon population and lasing continues. Estimate the final width W of the beam due to diffraction spreading. Stimulated Brillouin Scattering In Section 5 we discussed ordinary Brillouin scattering in which light is scattered by an acoustic wave. (From E. In each case distinguish between polarization modes. Curve (a) is rather steep on both sides of its maximum at 550 nm. Without emphasizing this, we have been using meridional rays in all our diagrams. If the manufacturer provides rulings a. In Figure 6c, it is clear that for distinct vision, the hyperopic near point is farther away than the normal near point. 2 The linear electro-optic tensor pij is defined by the relation e11>n2ji = © ipijEj , with i = 1, 2, 3, 4, 6 and j = x, y, z. Notice that the result is independent of wavelength. Nevertheless, the Kirchhoff theory suffices to yield accurate results for most practical diffraction situations. This fluid has a refractive index of 1.336, almost equal to that of water (1.333). This phenomenon is essential in the transmission of light through fibers by a series of total internal reflections. For the highest spectral purity, particular isotopes of the gas are used. A right-elliptically polarized wave traveling in the z-direction. 18 A soap film is formed using a rectangular wire frame and held in a vertical plane. If c1 and c2 are independently solutions of the wave equation, ${2c = 1 0 2c y2 0t2 then the linear combination, c = ac1 + bc2 where a and b are constants, is also a solution. We shall take the equivalent focal length of the two-lens system to be feq = f2 = - 1>C. The overall transfer-matrix elements are first determined by forming the product of the transfer matrices of the individual layers. Until the technique of making replicas—relatively inexpensive copies of masters—was developed, few research scientists owned a good grating. It is this last arrangement that we will discuss in the following sections. The radius of curvature of the spherical surface is 7.5 cm, and the glass has an index of 1.50. The combination v = 2pn is called the angular frequency, and the reciprocal of the wavelength k = 1>l is called the wave number. For concreteness, we consider the case of a parallel plate of thickness t and index of refraction nf surrounded by air on both sides. The interpretation is based on two considerations. 444 Chapter 20 Aberration Theory Applying the cosine law to the triangle BOQ in the geometric detail shown in Figure 5, we have r¿ 2 = r2 + b2 + 2rb cos u and introducing this expression for r¿ into Eq. (22) gives a1Q2 = c1r4 + 4c1b2 cos2 u + 2c2b2 + 4c1b cos u + 4rb3 cos u2 (23) From similar triangles OBC and SCP, in Figure 5, we see that the distance OB = b is proportional to the height h¿ of the paraxial image P, above the optical axis. Lens L2 acts as a Fourier-transform lens. This technique is utilized in the Fresnel (book) (Figure 7). Aperture Spectral image S L1 L2 f2 L3 f f f Fourier Optics INTRODUCTION Two rather extensive areas in which the Fourier transform is central to applications in optics are treated in this chapter, although, necessarily, somewhat cursorily. Also, throughout most of this text we use the symbol I, rather than Ee , to represent irradiance.) Notice that the SI unit of luminous energy is the talbot, the unit of luminous intensity is the lux (lx), and the unit of luminous intensity is the candela (cd). Determine the radii of curvature of the outer surfaces of the lens, as well as its resultant focal length for the D, C, and F Fraunhofer lines. The free spectral range or order may be determined by increasing fringe and much to describe the modulation that is accomplished by varying the refractive index of a material through the use of an applied electric field. When two or more light fields of very large amplitude mix together in a material, the resultant light field may not be simply the superposition of the individual fields. A series of such double layers increases the reflectance further, and the structure is called a high-reflectance stack, or dielectric mirror. Distances are directed, positive or negative, by a sign convention that makes distances directed to the left negative and distances to the right positive. Many photodiodes used in the visible to near infrared region of the spectrum use p-i-n junctions. No other light source, with or without the help of lenses or mirrors, generates a beam of such precise definition and minimum angular spread. Notice that the y0 component of B must reverse on reflection. The exponential term in Eq. (66) merely reflects the "more-or-less" plane wave nature of the solution. With a given gain medium one can increase the output irradiance by increasing the pump density Rp2 , since this increases the small signal gain coefficient g0 . The situation is sometimes described by referring to the reference wave as a carrier wave that is modulated by the signal wave from the scene. For example, the C coefficient 1C1 accompanies the term h¿r3 cos u, where h¿ is to the first power, r is cubed, and cos u is to the first power. (a) Viewing assembly. For N small, however, N odd can be handled by taking the origin at the center of the central slit. voltage across the cell. We note that wavelength separations larger than 5 nm or so can be measured with a Fabry-Perot cavity provided that one has additional knowledge of the wavelength separation so that the difference in mode number associated with adjacent transmission peaks can be unambiguously determined. A conservative estimate2 of fiber resolving power, RP, is given by RP l>lmin=>l = 500 nm>2 (1) Thus, a 5-nm fiber, for example, can produce a high resolution of about 100 linescm. For a shift of fringes of magnitude εx (Figure 20b) the change in m is given by εm = εx>x, resulting in d = 1εx>x21l>22 (46) Since both fringe spacing x and fringe shift εx can be measured with a stable microscope—or from a photograph like that of Figure 20—the film thickness d is determined. 133 Properties of Lasers Solution The output power P is the rate of energy emission. The hologram, like the holographic grating, operates as a dispersing element. 16 A small, monochromatic light source, radiating at 500 nm, is rated at 500 W. (Hint: the spectral energy density in (a) includes the energy in field components moving in all directions while the spectral radiance accounts for the power moving normally away from the blackbody surface.) 2 Consider a monochromatic electromagnetic field traveling with speed c in a given direction. Here, b is a constant of dimension m-1. Points of maximum strain are made visible by light transmitted through crossed polarizers when the stressed sample is positioned between the polarizers. For example, if p = q = 20 cm, L = 10 cm, and l = 500 nm, then y = 0.632 for a slit width of 0.01 cm. Recall that in the Littrow configuration, light is incident along the normal to the groove faces. To understand the interaction of light with individual atoms and molecules, it is important to keep in mind that EM waves gain and lose energy in discrete amounts proportional to the frequency of the radiation. Hernandez, G. Thus rays spread out radially in all directions from object point O, as shown, in real object space, which precedes the first refracting or reflecting surface of the optical system. What is the phase difference between the TE and TM modes after both reflections, where the angle is 5% below and above the correct value? Only the first, however, represents the important case of a periodic wave. In the CRIN fiber, a process of continuous refraction bends rays of light, as shown. 5 0.625 cm 2m Figure 19 Problem 3. This service is performed by a semiconductor device, most commonly a PIN diode, an avalanche diode, or a photomultiplier. Only electromagnetic fields that have frequencies near the resonant frequency of the lasing transition (and so can experience significant gain) and very near a standing wave frequency of the cavity (and so experience low loss) will be present in the laser output. Regions may overlap, as in the case of continuum from X-rays to gamma rays. When the function f(x) is such a discrete set of sample points, the continuous Fourier transform reduces to a discrete Fourier transform. Wolf, Parrent, Jr. Theory of Partial Coherence. The geometric relations simplify in this case. In the ideal polarizer, the transmitted light is linearly polarized in the same direction as the transmission axis. The lifetime broadening contribution to lineshape function g1n2 is related to this broadened spectrum. These waves would seem to disappear at the right node and be generated at the left node of each pulse. In Figure 16f the steady-state operation of the laser is illustrated. As mentioned, a good Fabry-Perot interferometer may have, overall, a resolving power in the range 106 - 107, whereas the resolving power of a good diffraction grating is in the range 105 - 106, an order of magnitude lower. It is nevertheless helpful in some cases to think of prisms as functioning approximately like one-half of a convex lens. Before investigating the effects that the Hermite functions g1j2 and h1h2 have on the transverse nature of the beam irradiance, let us examine the consequences of the third condition imposed on Eq. (52), 0p 2k = C1 - C2 - 2k q 0z (62) where C1 = 4m>w2 and C2 = 4n>w2. Stereoscopic Vision The ability to judge depth or position of objects accurately in a threedimensional field is called stereoscopic vision. A notable example is the He-Ne laser, where the laser-active neon (Ne) atoms are excited by resonant transfer of energy from helium (He) atoms in a metastable state. cm2 # sr Solution a. Describe the image of the glass beads. Suppose that the line image has a radius of curvature of 5 cm, a refractive index of 1.60, and an axial length of 2 cm. For oblique incidence, however, results must be calculated for each polarization. 12 What must be the temperature of a graybody with emissivity of 0.45 if it is to have the same total radiant exitance as a blackbody at 5000 K? This example shows how optical filtering is applied to the extraction of desired periodic signals from background noise or, on the other hand, to the elimination of periodic noise from a desirable signal. If optical fiber is used instead, with a loss rated at 4 db/km, how long can the transmission line be? A QWP is allowed to intercept the beam first with its OA parallel to the TA of the polarizer. Determine the radiant flux delivered to the film. (c) Diffraction pattern due to a single slit. Snell's law, which we have taken as the first step in the analysis of the optical system, the fringes are observed by light laterally by 3.4 mm. Calculate (a) the wavelength of the light and (b) the coherence time of the source. Assume that 5% of the lamp energy is converted to light. Of course, spontaneous emission occurs in addition to the stimulated processes and so spatial and temporal coherence properties of laser light may be emitted by an absorbing medium, but this light is emitted in any direction and with any frequency within the linewidth of the transition. The more massive nuclei can be considered stationary since they are unable to respond to the rapidly changing fields in this spectral region, but the electronic field at the input of the filter must be a monochromatic plane wave. One should also show the ray diagram for the same system with a smaller aperture. Equation (65) and magnification 3 at a distance of 10 cm. Figure 10 shows the construction of a double lens. In the general case, L has degrees of freedom, and its degenerate mode are equivalent function as an eyepiece. For low magnifications, with focal lengths in the range of 8 to 64 mm, achromatic objectives are generally used. The net phase change is made up of two parts, the optical-path difference є and the phase change 2fr that occurs due to the two total reflections at points A and B. Since this direction is the same as that of the cross B product of the orthogonal vectors, E and B, we can write, finally, B B B S = e0c2E * B (40) Note that since this relation involves the product of two waveforms, it does not hold for waveforms written in complex form. If the film is of varying thickness t, the optical-path difference є = 2nf t cos ut varies even without variation in the angle of incidence. 304 Chapter 12 The Diffraction Grating Plate Concave grating Echelle grating Figure 9 Side view of the echelle spectrograph. When the signal is internally amplified by secondary electron emission, the detector is a photomultiplier; see Figure 3. 21 Show that one can arrive at Eq. (32) by taking the origin of coordinates at the midpoint of the central slit in an array where N is odd. 16 The reflectance R (see Problem 15) of a Fabry-Perot etalon is 0.6. Determine the ratio of transmittance of the etalon at maximum to the transmittance at halfway between maxima. Figure 27 Construction of Huygens and Ramsden eyepieces. 192 193 Optical Interferometry 1 THE MICHELSON INTERFEROMETER The Michelson interferometer, first introduced by Albert Michelson in 1881, has played a vital role in the development of modern physics. Thus, in this case a varies from a certain negative value to q . First, find the irradiance at the film due to the superposition of a plane and a spherical wave. Laser systems with moderate or high output powers can be fabricated in such a way that they will emit a single longitudinal cavity mode. For example, by a partial derivative at the resultant wave is simply the sum E01 + E02 of the amplitudes of the individual waves. Since E-oscillations in the upper glass E 1E2 interact more strongly with the electrons, the speed y of these component waves is reduced, that is, y 6y1 . Representing I with the help of Eq. (47), we conclude B B I 0E 1 e0B a bE = 2p 2a b = 2(2 - 1) - 0y 0t c e0c 2B (53) For plane, harmonic waves given by E = E0ei1kz - vt2, the appropriate time and space derivatives required by Eq. (52) can be calculated to give k2 = v2m0 e2 + ia k 2 = a (54) where we have also made use of the fact that c2m0 e = 1>c2 with the permeability of vacuum. (a) 6C * (b) 8.68 cm 25. The indices are n400 = 1.52255 + 14825 nm22= 1400 nm22 = 1.5557 n500 = 1.5255 + 14825 nm22>1500 nm22 = 1.5448 n700 = 1.5255 + 14825 nm22>1700 nm22 = 1.5353 b. Wavelength-division multiplexing (WDM) is a means of combining 40 or more signals, carried in different wavelength channels, so that they propagate together through the same fiber. 196 Chapter 8 Optical Interferometry This means that the fringes are more widely separated when optical-path differences are small. Laser systems with gas or liquid gain media can be cooled by the same techniques, or by flowing the lasing medium itself through the cavity and cooling it before returning it to the cavity where it can again be pumped. The same conditions may lead to the enhancement of one visible wavelength interval or color at the expense of the others, in which case interference colors are produced, as in oil slicks and soap films. z p. In - nP2 + 0 (10) Notice that the linearly polarized light is rotated through an angle that is proportional to the thickness z of the active medium, as verified experimentally. This turns out to be much more narrow than the spread of the Doppler effect for light. Other interferometric systems, such as that shown in Figure 7b, are essentially those used to produce holograms. Once the lines, the atoms spontaneously decay, through various chains, back to the ground state 89 . Determine the radiant exitance, radiant intensity, and radiance of the object. Notice that this relationship produces the correct sign of s2 , as in Figure 20, and also when the intermediate image falls inside or to the left of the lens. A measure of this bending is the Coddington shape factor s, defined by s = r2 + r1 r2 - r1 (27) where the usual sign convention for r1 and r2 is assumed. There is one relative motion between them that determines the frequency shift in the Doppler effect for light. Inspection of Eq. (52) indicates that for a given z, that is, for a given transverse plane, the first bracketed series of terms, the g-expression, is a function of x alone; the second, the h-expression, is a function of y alone; the third is independent of both x and y; and the fourth is identically zero, since q = q0 + z is the propagation law that we continue to take to be valid. Gamma rays have very short wavelengths in the range from 0.1 nm to 10-14 nm. Optical Image Formation and Processing. Film Laser beam Figure 4 Cylindrical film surrounding the subject records a 360° hologram. The allowed energies of electrons in the wide variety of types of atoms and molecules cannot be summarized in a simple formula. 32 A ray of light traverses successively a series of plane interfaces, all parallel to one another and separating regions of differing thickness and refractive index. Thirer, Atlas of Optical Phenomenon, Plate 40, Berlin: SpringerVerlag, 1962.) (b) 360 Production of Polarized Light change in thickness. When etched, the interference pattern is preserved in the form of transmission grating grooves whose transmittance varies gradually across the groove in a sinusoidal profile. These nonlinear phenomena require an extension of the linear theory that allows for a nonlinear response of optical materials to the electromagnetic radiation. This permanent periodic poling produces the alternating sign of x2 needed for QPM. That is, ETOT = nhn = nhc>l The number of photons n emitted in 1 s is therefore n = ETOT l J 1 = 15 * 10-7 m2 = 2.5 * 1018 hc 1 6.63 * 10-34 J # s2 13 * 108 m>s2 For this light source, the source size is not critical. But coherence length is not a concern for this light source, and the photons are not used for interferometry. Zoom Lens 18 (a) 15 (3) Show that the wavelength c = 1 are related by a variation in the angle of refraction. 20 and of the hologram is referred to as be noticed. (3) and (4) for lateral aberration by and longitudinal aberration br, the spherical aberration for each of the lenses or surfaces in an optical system may be calculated. As bonus: by 40C40y, 3 a¿ s¿, s¿ da + n2 + n2 dr + n2 + n2 dh = dr = 40C40y 2 2 n2 Example 1 Axially collimated light enters a glass rod through its end, a convex, spherical surface of radius 4 cm. The second prism serves to reorient the transmitted ray along the original beam direction. In Example 4 we consider the effect of using reading glasses on the vision of a person with presbyopic eyes. The distances L and L¿ are related, as suggested by the geometry in Figure 9, by sin wc = n2 / L = m n1 / L¿ Thus, the times of flight for the two rays taking the extreme paths between points A and B differ by the time interval dt, given by dt = tmax - tmin = L¿ L L n1 - 1b = a y y y n2 where y is the speed of light in the core. Figure 10 illustrates the principal B I E E L Plane of polarization rotates inside material Incident polarization (horizontal) Exit polarization (vertical) B B B 90 Head-on view Faraday rotator Head-on view 45 Figure 9 Faraday effect producing rotation of the plane of polarization. Equating Eqs. To project a larger image on the retina, the simple magnifier is inserted and the object is moved physically closer to position (b), where it is at or just inside the focal point of the lens. A particularly elegant means of Q-switching involves the insertion of a saturable absorber into the cavity. Perry, and Richard W. Three exact values of x for which A1x2 = 0, and these are zero or finite at all x. Notice that (b) OA OA (c) Figure 16 Polarizing prisms. For example, zinc has two outer-shell electrons. In (b), the incident and reflected beams are separated for clarity. hgh f1 = -11.51 cm; f2 = 15.31 cm; r = 0.400 cm; s = -1.16 cm; s = 4.20 cm; w = 2.64 cm; si = 18.9 cm from H2 ; hi = -1.18 cm (a) f1 = -20.15 cm = -f2 ; r = 10 cm = -s; v = 10 cm = -w (b) Image is inverted, real, 61.38 cm from sphere center and m = -2.05 x (a) y = 1 cm; s = -5.73° (b) A = 1 - s/0; B = 10/3 + 2s/3; C = -1/10; D = 2/3 (c) s = -4.17 cm; r = 12.27 cm, r = -0.83 cm, s = -27.17 cm, r = 0.66 cm, s = 13.33 cm,f2 = 4.33 cm f1 = -20 cm, f2 = -20 cm, p = -30 cm, q = +10 cm, r = -10 cm, s = -10 cm f1 = -16.7 cm, f2 = +23.3 cm, q = +18.7 cm, p = +18.3 cm, r = +4.67 cm, s = +4.67 cm (a) A = 1 - 2p, B = 2 - p, C = -2/p, D = -2p (b) Input and output planes fall at conjugate object and image positions. A is identical with the linear magnification. Figure 16 Three examples of a phaseconjugated replica of an incident wavefront produced by an ordinary mirror. To see this, take the average over a range of angles q as generalized to include a change of phase for a fixed aperture. where the phases are given by n2 = 4 f] Ned a 2 med) yj - ej - igjy (39) where gj , called the oscillator strength for the resonance vj , represents the fraction of dipoles having this resonant frequency. If the top edge of the beam strikes the film at x = 0, then w is a linear function of distance x along the film plane, since w = a 2p b 4 = a b x u = u 11 (2) This may be called a phase relative to the tilt of the film plane relative to the reference beam and appears as an exponential factor in Eq. (19). ER = (revolve (3) If ER = ei(kx-vt) is the complex field in the plane of the aperture (Figure 14), then the system reference beam. Notice in the time that is evenly partitioned the distribution equation for S and V of the reflected light at different points of the film and u = u1, y2 is a complicated function due to the variation in phase of the light reaching the film from different parts of the subject. The incident beam of roughly collimated light is divided into two beams at beam splitter BS. It was the double-slit experiment, in which an opaque screen with two small, closely spaced openings was illuminated by monochromatic light from a small source. Match the arrangement, showing the observation of fringes from two rays combined at the aperture of the telescope. A detector is situated on axis at a distance of 20 cm from the aperture plane. In a few days we began to wonder, however, by determining which of the actual elements in the given system—in this case, A, L1, or L2— has an entrance pupil that confines rays to their smallest angle with the axis, as seen from the object point. Since from Eq. (44), n1 cos wc = 2n21 - n22 = N. Consider a 1-meter-long linear cavity with a mode spacing nfsr = 1.5 * 108 Hz. Let this cavity contain a gain medium of bandwidth 1 GHz pumped so that at the frequency of the transition line-center n0 the small-signal gain coefficient g01n0 2 is twice the threshold gain coefficient gth . Combining Snell's law n1 sin u0 = n2 sin wt with the trigonometric relation ut = 90 - up , we arrive at Brewster's law, up = tan-1 a Figure 5 Pile-of-plates polarizer. In this and following chapters, several such applications, considered under the general heading of interference, are presented. Mirror P Q M O N Q P (a) P Q M O Q N P (b) Figure 6 Spherical aberration (exaggerated) in (a) a spherical mirror and (b) a thin lens. It is sufficient in what follows, therefore, to treat only one of these functions. Arguing from the Fourier series representation of the data to represent this kind of aperture function, it is clear that greater and greater numbers of increasingly higher harmonics are required to define the discontinuous behavior in the diffraction spectrum higher than m = 1 do not appear. Chapter 4 Ghatak, Ajoy K. and the ray-transfer matrix representing the entire optical system M = MNMN - 1 A M2M1 (14) We apply this result first to the thick lens of Figure 8, whose index is nL and whose thickness, measured along its optical axis, is t. See for example, Amnon Yariv, Optical Electronics, 3d ed. 382 Chapter 16 Holography of the change at specific locations, as in the case of Newton's rings. Figure 8 illustrates the concentric circle. The relationship of crystalline asymmetry with refractive index and the speed of light in the medium may be understood a bit more clearly by considering the case of calcite. Plastic fibers are less expensive but not nearly as transparent. (a) Cartesian ovoid images O at I by refraction. (b) In general, when magnifiers are used to aid the eye viewing images formed by prior components of an optical system, they are called oculars, or eyepieces. They are also used to analyze the degree of polarization in light. These allowed energies EvB is associated with the vibration of a diatomic molecule are given by EvB = k = 1=2hf Here, k is the vibrational quantum number and can take the values k = 0, 1, 2, and f is the resonant frequency of the vibration. c1y, t2 = A sin1ky + vt2 + A sin1ky - vt2 + With the help of complex exponentials, show that c1y, t2 = 2A cos1ky2sin1vt2 15 The energy flow to the earth's surface associated with sunlight is about 1.0 kW>m2. In the blazed grating (b), they are separated. Lasers. This abruptly depends directly upon the resolving power of the eye or its minimum angle of resolution of two closely spaced objects or points. Over this range, the energy density function is nearly constant and can be taken to be r1n0 2. The mirror image of the image point when the elements are. Coordinates. We shall use the term free spectral range to refer to the separation between adjacent transmittance peaks regardless of the choice of independent variable but take care to symbolically differentiate between the free spectral ranges in the different modes of operation. (c) Overfilled systems typically have pulse widths on the order of a cavity lifetime tp = 1>v since the pulse must leak out of the cavity. It has also been suggested that robots could identify and be directed toward appropriate objects in the same way. James, J. The line spectrum of a weakly excited dilute gas is sometimes called the fluorescence spectrum of the gas. Vectors in Table 1 have all been normalized. Suppose the Fourier transform is a normalized form. Show that at z = 0, E1 + E2 = 2E0 at times given by t = n>dn, where n is an integer. 5, 6. The requirement that the component of the electric field parallel to the boundary plane be continuous at the boundary then gives E + Er = Et (12) 494 Chapter 23 Fresnel Equations The magnetic fields associated with the electric fields of Figure 1 have the form, B = IB cos uxN - B sin uzN 2ei1k # r - vt2 B B Br = Br cos urxN - Br sin urzN 2ei1kr r - vt2 Bt = Bt cos utxN - Bt sin utzN 2ei1kt # r - vt2 B B (13) Bt = Bt cos utxN - Bt sin utzN 2ei1kt # r - vt2 B B Continuity of the parallel components of the magnetic field requires that the field amplitudes be related by B cos u - Br cos u = Bt cos ut (14) where we have made use of Eq. (8). In this case, the total irradiance Ia at point P is proportional to the square of the length of the phasor Ea , as shown in Figure 11. The presence of the third mass m in the denominator of these equations shows that electronic oscillations are more important than ionic oscillations in determining the index of refraction. How many pixels would be in such a CCD array of dimensions 2 cm * 2 cm? Perhaps the simplest means of producing pulsed energy output from a laser would be to pulse the pump—that is, turn the source of laser energy on and off. In this case, you can simulate the construction of a c e 0 b 1 dc d = c d (14) Of course, the corresponding algebraic equations are now a112 + b102 = 0 a112 + d102 = -1 The equations in Eq. (14) are satisfied by a = 0 and c = 0. The simplification we make is to neglect the thickness of the lens in comparison with the object and image distances, an approximation that is justified in most practical situations. In these cases, w¾>2 = p>2 and the resultant field takes the form ER = E2E0 sin kx2cos vt (15) which represents a standing wave. Thus, I2 = I0 where I0 is the maximum value and represents an estimate of the useful length of a crystal 4 Ammon Yariv, Optical Electronics, 3d ed. The reference field E0 is large compared with the variation of intensity. (b) A spectrally narrow input is reduced to about 0.4 of its maximum value and so represents an estimate of the useful length of a crystal 4. The determine the coordinates of the elements A, B, and C of the general system vector (Eq. 9), representing polarized light, that lead to the general case of linearly polarized light; (c) elliptically polarized light with major axis aligned along a coordinate axis; (c) circularly polarized light. The transmittance of the output mirror is T3 = 0.04. 32 Chapter 2 Geometrical Optics trace, depending on the object location before or after points C and F, and on the geometry of the mirror surface, concave or convex. Parallel plates, such as the one studied here, can be used as Fabry-Perot interferometers. The method of pattern recognition just described is perhaps the simplest to understand, but many other techniques with various advantages have been developed. 4 Plane waves of monochromatic (600-nm) light are incident on an aperture. The results of Example 4 indicate that a large number of equally spaced wavelength channels could be demultiplexed by a system of Mach-Zehnder interferometers. More generally, the survival factor S should include factors describing each process that reduces the irradiance of the beam as it traverses the ring. The coefficients A 21 , B21 , and B12 are characteristic of the two energy states. Beyond resonance, however, when v > v0 , P and E have opposite signs, indicating a phase difference of p. For the normal ray, on the other hand, due to the B E-component perpendicular to the OA, everything is normal; the ray obeys B B B B B Snell's law, the Huygens' wavelets are spheres, K E, k T S, and the ray is perpendicular to its wavefront. (a) Converging lens (positive focal length). Hinge, Huygens' wavelets, (1) where E u - v2 = E0y, mE0x p u(vt - ky) (11) The equations as specified must satisfy rule 28. This provides a greater phase-space portrait; in other words, the Fourier transform mapped by to the formation of a narrow pulse. 0 is the mode index, x = p>2 and Δ 2p2 - s22 b. The Faraday effect can be used for light modulation, although it is difficult, practically speaking, to modulate a magnetic field at very high frequencies. (1) ' Ex = E0xei1kz - vt + wx2 (2) ' Ey = E0yei1kz - vt + wy2 (3) and ' ' Here, Ex = Re 1Ex2 and Ey = Re 1Ey2. To understand this visual through one aspect in Figure 3. Let another way of saying is the standard through shaping of their surfaces, to produce a net power of the doublet that may be either positive or negative. In Figure 12, three experimental sample interference patterns are shown, produced by a Michelson interferometer using various spectral inputs. Gabriel, Robert, Lloyd, Aperture 6. The lenses are equal. The lenses of a lens in front of the eye's lens are being focused. The blazed wavelength is given by Eq. 3. Show that the first order of the spectrum is at 0.218 cm (b) 0.218 cm (b) 0.135 mm (b) 139 496 nm 614 5. The focal lengths and powers of the lenses differ. The reflection from a plate of thickness t is located in an apparent position. The Jesuit Francesco Grimaldi had noticed the fine structure in the edge of a shadow, a structure not explainable in terms of the rectilinear propagation of light. Recall that a laser system converts pump energy into laser output and so the average power output of a laser is always less than the average pump power. Figure 13 shows that M for numerical dispersion becomes zero for longer wavelengths. The state of polarization of the light can most easily be tested by a second dichroic polarizer, which then functions as an analyzer, shown in Figure 1. It is from this axis that the displacement yi of the rays of the oblique pencil would have to be measured to show a typical photograph of the x (a) x (b) Figure 20 (a) Photograph of interference fringes produced by the arrangement shown in Figure 19. Thus the total energy emitted by the lamp is the product of the power and the time interval. In summary, the small-signal gain coefficient g0 and the threshold gain coefficient gth for the laser field to grow in the cavity. Thus either maximum intensity points along the axis are to be found at R21 , all fn = n odd (23) Example 2 What are the focal lengths for the zone plate described in the preceding example? The two light beams of the fiber-optic Mach-Zehnder interferometer are positioned beyond the end faces of the tube. Again, if the source is small, then real, nonlocalized fringes appear in the light emerging from the interferometer, as for either of the two virtual images of the source in M1¿ and M2. The field of view in object space can then be described by a, the angle subtended by the entrance window at the center of the entrance pupil. 331 Fresnel Diffraction PROBLEMS 2 A 3-mm-diameter circular hole in an opaque screen is illuminated normally by plane waves of wavelength 550 nm. (20) and (22). Calculate the degree of polarization P of the transmitted beam, given by 20 When a plastic triangle is viewed between crossed polarizers an image. To a first approximation the field in the focal plane of the lens is described as the sum of a series of alternating transmission and absorption bands is observed. Coherent sources are the virtual images S1 and S2 of source S, formed by reflection in the two halves of the prism. t = (i n1 x/c 1/2 1.25(x2 + y2) + 70(x2 + y2) - 135x + 800 = 0 4.00 cm 5 ft, with top edge of mirror at a height halfway between the person's eye level and the top of the person's head The ray emerges from the bottom at 45°. With these relations and since ' the beam irradiance is proportional to the square of the magnitude of Emn , Imn = I0 a b 2 w0 H 2 m1 + 2 2 H 2m1x>2H 2m1y>2e - 2ax + 2 y2 Amnon Yariv, Quantum Electronics 3d ed. In such a case, d is a constant 167 Interference of Light and the interference term takes the form, 2211I2e0cn1k1x2 - v12 + f111t2 - f11t229 = 2211I2 cos1kx2 - s122 = 2 2I1I2 cos d Even if the electric fields travel paths that differ in duration by a time dt, the phase difference resulting from this time difference is constant over time as long as the source is monochromatic, f11t2 - f11t + dt2, will still be nearly zero so long as dt is less than the so-called coherence time, t0 , of the source. A photograph of the pattern is given in Figure 14d. Referring to Example 2 in which the external beam waist is focused at / 0.06 m with a waist size wf2 = 0.54 mm, use Eqs. The plot clearly shows that interaction points approach the vertical lines defining midpoints more closely as N increases. (Oriel Corp., General Catalogue, Stratford, Conn.) (a) (b) Figure 7 High-intensity, compact short light source. In the region of 1 to 8 mm, the semiconductor compounds PbS, PbSe, and PbTe (lead telluride) possess a large photoelectric effect and greater sensitivity than the PbS detector. So the exit pupil EnP is located between the lenses, 5 cm to the left of L2 or 1 cm to the left of L1 . Equation (1) gives the energy of a photon as hn. If the quality of the image is to be improved, however, ways must be found to reduce the aberrations that arise from the presence of rays deviating, more or less, from this ideal assumption. Indeed, requiring energy conservation in a Mach-Zehnder interferometer is one way to prove that beam splitters in real systems have reflection coefficients from opposite surfaces that differ by a factor of - 1. Conceptually, account for the missing pump events. This matrix is A B C D D 1 Z2 0 1 TD T = D Z2 2 + 1 Y2 1 0 1 Y2 C 1 Z2 1 T D 1 Z2 Z2 - Z1Z2 f 1 T 2 1 + Z2 f 1 f1 T (44) Then the ABCD propagation law gives q2 = a1 - Z1Z2 Z1 b q1 + a Z1 + Z2 b f f Z1 1 + q1 + 1 a b f f1 (45) Using the rule of Eq. (17) and noticing that the radius of curvature of the beam at the beam waist is infinite, we find q1 = - i pw201 at Z1 and q2 = - i pw202 at Z2 1 Using these relations in Eq. (45), we obtain a rather complicated equation that contains the desired unknowns, Z2 and w02. Thus, a wavelet of radius JN and its segments subtend a small angle with the axis. Suppose the source is the sum of these two waves. 5 PHASE CONTRAST MICROSCOPE Fourier Optics where n is an integer. The sharpness of the image of the distant point object—a star, for example—is, then, limited by diffraction. Turning on the acoustic wave deflects the light at the Bragg angle, steering it to the center of the far-field transmission. (a) Determine the distance between the first two of the fringes. Typical values of the focal lengths and the zero or other integer. Even rays that are entirely reflected or diffracted by either the tuning element or the optical medium. Draw a picture showing the magnification of the lens. 394 Chapter 17 Optical Detectors and Displays voltage across a pixel, so that the light is neither completely blocked nor transmitted, or by pulsing the voltage at each pixel, so that the length of the transmission pulse leads to differences in perceived brightness of the pixel. 4 Using the Fourier transform, determine the power spectrum of a single square pulse of amplitude A and duration t0 . Notice also that pulse broadening due to material dispersion is much smaller than that due to modal distortion. This pattern may be manipulated in turn, using masks or filters to modify the final image produced by a second lens in a process called spatial filtering. The two wave vectors and as well as the wave vector k, of the diffracted light beam, are also shown. Hydrogen atoms in high-energy states have a larger orbit radius. In addition, microwaves play an important role in radar systems both on the ground and in the air, in telecommunications, and in spectroscopy. M1J2 = J2 12 1 M2 M1 4 112 Figure 14 Problem 34. some of this beam, which we call the subject beam, also strikes the film, where it interferes with the reference beam and produces the hologram. The Balmer series refers to the light emitted from transitions from excited states with U 3 to the n = 2 energy state. Presbyopia can be remedied in some patients by using CK to correct the refractive power of one of the eyes for near vision while the other eye is left untreated and is used by the patient for middle-to-distant vision. In each case, the light is propagated in the positive z-direction. The final form of U1x, y, z) can then be used in Eq. (6) to give a manageable form for the Gaussian beam solution to the wave equation, ' w0 2 2 2 - be-r >w 1z2ekr >2R1z2e - i tan 1z>z02ei1kz - vt + f2 E = E0 a w1z2 (24) where R1z), z0, and w(z) are given by Eqs. This pattern strongly suggests that the gain for the equation as is shown in the first line of the final drawing. A simple model in which electrons are held by springlike forces to a fixed nucleus is the following: Gain Saturation in Homogeneously Broadened Media It is important to note that the expression for the gain coefficient given in Eq. (37) is valid only for homogeneously broadened media since the derivation of this relation implicitly relies on the assumption that all atoms participating in the interaction with the light are of the same type. A linearly polarized wave traveling in the x-direction. The halogen vapor functions in a regenerative cycle to keep the bulb free of tungsten. Thus, the wave-particle duality came full circle. At the center of the pattern projected on a screen, the irradiance is Imax . The defined angle a is taken here as the angle of incidence, thereby indicating that the aperture of the prism, a single structure. The result is that point objects are not imaged as points but rather as small blurred lines. For the situation shown in Figure 12, calculate the dispersion dy = 500 * 10-9 m s = 3.125 * 10-8 s a 20 * 10-9 m l = 3.125 * 10-3 a 16 10 so that for 4 cm, ch 1 d2 = 3.125 * 10-8 a b = 10-7 (a) 0.05 m That is, this Fabry-Perot interferometer easily resolves a fractional difference in wavelength of less than one part in a million. In an inhomogeneously broadened system pumped so that g0 = 2gth , all modes within 2/3 of linecenter will be above threshold (see, for example, Figure 12a). A list of useful refractive indices is given in Table 1. To understand its design, refer to Figure 36. Entrance Pupil EnP: There are no optics to the left of the aperture stop A, so it serves also as the entrance pupil EnP. Since L depends only on n and r, it is cylindrically symmetric about the z-axis. This region has lateral dimensions of l and longitudinal dimensions of l relative to the source and thus occupies a volume of roughly l2s It around the point P. The rates associated with these processes are valid for the case of interaction with a nearly monochromatic laser field of frequency n0. Let us express the situation more precisely in mathematical terms. 3 Write out the second-order terms of the expansion of the three-beam interaction, where the beams are plane waves of the form E01 , E02 , and E03 and frequencies v1 , v2 , and v3 , respectively. What are the diameters of the holes that produce (a) the first two maxima and (b) the first two minima? The rods, stimulated by low-level light signals (scotopic vision), contain pigment of only one kind, called visual purple. 7 CHROMATIC ABERRATION The final aberration to be discussed is not one of the Seidel aberrations, which are all monochromatic aberrations. 21 Image and object distances for a spherical reflecting surface—in addition to satisfying the equation n1 - n2 n2 n1 + s s¿ R — must satisfy the condition m = 1 1 1/2 ... + 11s2 = 11s2. One example is the Pellin-Broca prism, illustrated in Figure 17. Its displacement of the origin is zero at time zero. Similarly, the image distance MP¿¿ is less than the distance NP¿¿ . (Prentice Hall, Inc., 1998). In Problem 2. There we found that the two product functions could be interpreted separately as diffraction from a single slit and interference from multiple (negligible width) slits. To model real sources, Eqs. These possibilities have already been discussed in the previous chapter, where we treated the various interference fringes that can be formed by a parallel film of refractive index n. Then 2 2 x b + 2 x = 1 - 0.9 * 10-2 x = - 5.19615 A 1 A In 1951/1200 * 10-92 329 Fresnel Diffraction Similarly, y2 = 0.57735. The same principle can be stated more formally as follows. Figure 13 depicts extreme cases illustrating the situation. The ability of diffraction gratings to direct light of different wavelengths in different directions has been used in several other applications. The abbreviations read as follows: H.N.P. = hyperopic near point; N.N.P. = normal near point; H.F.P. = hyperopic far point. That is, the overall effect is that the low-frequency wave serves as an envelope modulating the high-frequency wave, as shown in Figure 9a. Treating this system as an ideal four-level system, estimate the saturation irradiance of the laser transition. The retina is particularly vulnerable to damage from radiation in the visible part of the spectrum and near infrared. The transmittance of the air film with thickness t is equal to the value calculated by the transmittance. 539 Optical Properties of Materials B B The dependence of P on E, as given in Eq. (11), can now be used to discover the conditions under which plane waves are able to propagate in a dielectric. Assume an average wavelength of 550 nm. Dispersion The minimum deviation of a monochromatic beam through a prism is given implicitly by Eq. (15) in terms of the refractive index. (27) through (30) for the case of external reflection with n = 1.50. The phases of the two components are given by w = k(x - vt + yp = kz - vt + ly) = [E E E E E E E E Figure 18 Superposition of left- and righthcircularly polarized light at different instants. In molecules, the energy states are also distinguished by the vibrational and rotational state of the molecule. The beam can be scanned back and forth across the screen, covering the entire screen 30 times each second. Still, the use of a large number of closely grouped harmonic components can still be characterized both by a phase velocity, the average velocity of the individual waves, and by the group velocity, the velocity of the modulating waveform itself. How much does 1n - n 72 vary between transmission bands to satisfy successive conditions for HWP retardation? Thus, AC = AC¿ and the distance traveled by the ray of light from A to B via C is the same as the distance from A¿ to B via C. A more complete analysis of this experiment must take into account the finite size of the slits. The energy of a photon is not a function of its speed but rather of its frequency. 24 Find the radii of curvature of the lens surfaces. In many common situations, there are several lines emitted by the atoms or molecules in one state. Even the brightest part of the light is taken by a simple cloud. The resulting angles of the five wavefronts are shown in the figure. Negative lens of focal length. The virtual image is formed at the point from which the rays diverge. The overall gain of the laser will drop to the threshold value. The focal lengths of the lens are given as positive. Applying the matrix method to the system, the intermediate image position is located to the right. The conjugate point is a virtual image. 0.1 nm < l < 10 nm Chapter 6 Bright light and dark lines are both conditions for minima and maxima respectively. Figure 20 The resulting image is formed on the retina. In this case the object lies at the focal point. Figure 26 shows the lens focusing in space. The light is absorbed to the active medium. This light of wavelength 1.06 mm of a Nd:YAG laser will be reflected off the retina. F1 Example 3 For a zero-order diffraction pattern, the secondary maxima are located at the positions indicated. The beam is said to be Gaussian. The function is illustrated in Figure 8. The eye may be injured by light reaching the retina at high power levels. 2 STANDING WAVES Most positive, a wave that exactly retraces its path produces a standing wave. The Fourier transform is known as the spectrum. The width of the spectrum is the inverse of the pulse duration. For normal operation, the pump rate must exceed the threshold. The eyepiece magnification is given by M = 25/f. The objective and the eyepiece work together. The field stop of the system limits the field of view. The focal length of a thin lens in air is the reciprocal of its power. What is the focal length of the lens? The absorption coefficient of the material as a function of wavelength. The emitted light will be linearly polarized. For this condition, the number of wavelengths is given by the length of the path divided by the wavelength. The focusing of a Gaussian beam by a lens is treated. Figure 22 shows the Gaussian beam waist in the focal region. The near point of the eye is 25 cm. Correct vision requires the image to be formed on the retina. A hyperopic eye has a far point behind the eye. Corrective lenses of positive power are used. The myopic eye forms images in front of the retina. The phase velocity exceeds the group velocity in a normally dispersive medium. Whenever the spectrum is symmetric, the output pulse is transform limited. This is the case of the Fourier-transform-limited pulse. The energy of the photons is distributed within the beam cross-section. The light source at center shows the result. Distances from the transmission axis in the case of the same series. Light and matter interact in different ways depending on frequency. 1 Derive the expression for the resolving power of a grating in the order m. 8 Use a computer to calculate and plot the phase shifts on reflection as a function of angle of incidence for n = 1.5. Determine the location and size of the field stop, FS.

I (b) Irradiance function I = I0 a: b: sin u: p 2p l a 2l a b2 sin2 a for the multiple slit of (a). 601 Characteristics of Laser Beams the defining equation for U, leads to 2iky 1 2ikx 1 1 0w g¿ 1 h– 1 0w h¿ 1 g– b + b + + 2 a a 2 g w q w 0z g w q w 0z h w w h ('''''')''''''* ('''''')''''''* 1 2 + 0q 0p 2ik k2 2 b = 0 1x + y22a1 - 2k 2 q 0z 0z q ('')''* ('''''')''''''* 3 4 (52) where the primes denote differentiation with respect to the arguments of g and h. Beam expander 2z0 2pw20 l Characteristics of Laser Beams 597 distance is the Rayleigh range z0 . At lower pressure and current, sharper spectral lines appear, and the background continuum is minimal. Thus, objects underwater, viewed from directly overhead, appear to be nearer the surface than they actually are, since in this case s¿ = 11>1.332 s = (3/4) s. Level 1 is the ground state and the nominal energy difference between the levels is E2 - E1 = hn0 . A detailed analysis of this interaction15 shows that the phase conjugate output beam has an amplitude that is proportional to the product of the amplitudes of the pump beams and the complex conjugate of the amplitude of the signal beam: (20) A 4 r A 1A 2A *3 Now, since the two pump beams are oppositely directed, the complex amplitudes on the right-hand side of Eq. (20) can be written as B # B A 1 = ƒ A 1 ƒ eik1 r , B # B B # B A 3 = ƒ A 3 ƒ eik3 r A 2 = ƒ A 2 ƒ e -ik1 r , so that B # B A 4 = ƒ A 1 ƒ ƒ A 2 ƒ ƒ A 3 ƒ e -ik3 r B Thus, k4 = - k3 and A 4 is proportional to the complex conjugate of A 3 . Holography alternating between minimum and maximum, then multiple diffracted images are possible. These fringes are virtual, localized fringes and cannot be projected onto a screen. The use of finite sampling intervals across a finite total sample width or window leads to limitations both in the resolving power of the instrument and in the minimum wavelength that is unambiguously handled by the transform calculation. Equations (27) through (30) are the Fresnel equations, giving reflection and transmission coefficients, the ratio of both reflected and transmitted B B E-field amplitudes to the incident E-field amplitude. Recently, the relation between the group and phase velocities of light signals has gained prominence as researchers have succeeded in preparing propagation media with dispersive properties such that the group velocity of the light pulses traveling in the nearly transparent media approaches zero.2 The dependence of index of refraction on wavelength can take a variety of forms, depending upon the nature of the medium through which the signal is propagating. The corresponding field amplitude at P¿ is then proportional to DE 7 OE and so IP¿ 7 IP . In a dielectric where B rf = 0, Jf = 0 also. Find the threshold gain coefficient if R1 = R2 = 1, R3 = 0.95, and T3 = 0.05. On the other hand, as t0 : 0, approximating a harmonic "spike," ¢v : q . The sum of all these contributions is the phasor A 1 . The radius R of the surface is also shown, passing through the center of curvature at C. TABLE 2 STANDARD RELATIVE APERTURES AND IRRADIANCE AVAILABLE ON CAMERAS A = f-number 1 1.4 2 2.8 4 5.6 8 11 16 22 1A = f-number22 1 2 4 8 16 32 64 128 256 512 Ee E0 E0>2 E0>4 E0>8 E0>16 E0>32 E0>64 E0>128 E0>256 E0>512 72 Chapter 3 Optical Instrumentation D a M O M N s0 s0 s1 Figure 22 Construction illustrating depth of field MN. The wire grid polarizes microwaves much as a dichroic absorber polarizes optical radiation. Information is not lost, as would be the case in other memory devices, where every bit of information has its own unique storage coordinates. Fringe distortion over the surface is found to be less than onefourth the fringe separation at any point. Consider again the wave represented in Eq. (20). In this configuration, the LCD transmits light. (Here, we have l1 632.8 * 10-9 m rounded down to an integer.) a. Recalling that the multiplication of matrices is associative but not commutative, the descending order must be maintained. 3.6 mm (a) 0.81 µm; 0.75 µm; 0.585 µm; 0.525 µm (b) 76%; 70%; 55%; 49% (a) 31.5 W (b) 1.26% Chapter 7 1. Determine the length (lens separation) of the instrument and its magnifying power for a viewer whose eyes are focused (a) for infinity and (b) for a near point of 30 cm. Similarly, if the wavefront radius of curvature R1z12 at Mirror 1 is equal to RM1 , the left-going beam will reflect from Mirror 1 without distortion and retrace its path to Mirror 2. Example 1 Find the approximate number of photons emitted in 1 s from a source that emits 1 W of light power at a wavelength of 500 nm. Electro-Optical Devices and Systems. For an object at infinity, incident rays are parallel and s¿ = - R>2, as illustrated in Figure 16a and b for both concave 1R 6 02 and convex 1R 7 02 mirrors. Stroke, George W. The use of three or more layer coatings makes possible a broader, low-reflectance region in which the response is flatter. If the original reference beam and the reconstructing beam are both collimated, what is the magnification of the holographic image, compared with the original subject? Field and Irradiance Patterns for Hermite-Gaussian Beams With the help of Eq. (66) we can sketch the transverse electric field and irradiance variation for several of the lower-order modes—small m and n— and thus predict the nature of the "burn" pattern. TABLE 3 KERR CONSTANT FOR SELECTED MATERIALS Material (l = 589 nm, room temperature) K (pm> V2) Nitrogen (STP) Glass (typical) Carbon disulfide 1CS22 Water 1H2O2 Nitrotoluene 1C5H7NO22 Nitrobenzene 1C6H5NO22 4 * 10-6 0.001 0.036 0.052 1.4 2.4 523 524 Chapter 24 Nonlinear Optics and the Modulation of Light Kerr cells can be used as modulators in the manner described for Pockels cells. This ray leaves point P as a ray parallel to the optical axis, strikes the mirror, reflects and passes through the focal point F of a concave mirror—as in Figure 17a and b. Solution According to Eq. (22), 1¢u2min = 1.221550 * 10-92 35 * 10-3 = 1.92 * 10-5 rad or about 4– of arc, using an average wavelength for visible light. Determine the percentage of light energy reflected in air from a single surface separating a material of index 1.40 for light of l = 500 nm. Many, however, preferentially start the trip back by a very fast (usually radiationless) decay from pump levels E3 to a special level, E2 . 603 Characteristics of Laser Beams The Hermite-Gaussian Beam Solutions Now, collecting our results for p, q, g1j2, and h1h2, and putting them all to' gether in the general expression for the electric field E1x, y, z, t2 as initially introduced in Eq. (6), we obtain finally ' w0 22y 1-x2 + y22>w21z2 22x Hm a b Hn a be Emn1x, y, z, t2 = cE0 d * w1z2 w1z2 w1z2 ('''''''')''''''''''* (66) amplitude ceik1x + y 2>2R1z2ei[kz - 1m + n + 12arctan1z>z02]e-ivteif d ('''''''')''''''''''* phase 2 2 It is standard to refer to the various waveforms distinguished by the different values of m and n as TEMmn modes. Assume a refractive index of 1 for the emulsion. The right side should be recognizable as the square of the sum of the individual amplitudes. As the screen is moved away from the aperture, the image of the aperture passes through the forms predicted in turn by geometrical optics, near-field diffraction, and far-field diffraction. These spontaneous emission events are then amplified by the action of stimulated emission within the gain medium. (Canrad-Hanovia, Inc.) 100 100 Mercury-xenon cathode tip 90 Relative spectral emission 142 90 80 80 70 70 60 60 50 50 40 40 30 30 20 20 10 10 0 0 240 260 280 300 320 340 360 380 400 420 440 460 480 500 520 540 560 580 600 620 Wavelength (nm) Figure 9 Spectral emission for Hg-Xe arc lamp. Consequently, the best solution is to use a single-mode fiber, 6 Actual values are somewhat better than predicted by Eq. (14) due to mode coupling or mixing (rays may switch modes in transit due to scattering mechanisms that, on the average, shift power from higher and lower modes to intermediate ones) and due to preferential attenuation (higher modes taking longer paths suffer greater attenuation and so contribute less of modulation in which a carrier wave is modified to carry a signal. It was first observed in 1971–1972 by researchers in the Soviet Union. Write a wave equation for this wave (a) that exhibits directly both wavelength and period; (b) that exhibits directly both propagation constant and velocity; (c) in complex form. Use the results of your experiment to estimate the diameter of your own pupils. In closing this section, we point out that both the saturation irradiance IS and the small-signal gain coefficient g0 are functions of the electromagnetic field frequency ν0, since they each depend on the cross section s, which in turn is proportional to the lineshape function g1n2. The light illuminates a double slit of spacing 0.1 mm. Calcite is birefringent in the visible spectrum, for example, and strongly dichroic in certain parts of the infrared spectrum. In Figure 15b, the pump energy (step 1) is supplied by an electrical discharge in the low-pressure gas mixture, thereby elevating ground state helium atoms to higher energy states, one of which is represented by the 21S level. Since the images S1¿ and S2¿ of the source plane in the mirrors must be separated by twice the mirror separation, the distance between Q1œ and Q2œ is 2d, and the optical-path difference p between the two beams emerging from the interferometer is p = 2d cos u (1) where the angle u measures the inclination of the beams relative to the optical axis. The design of an objective or an eyepiece is directly related to the performance of other optical elements in the instrument, often including a relay lens within the body tube of the microscope as well. Cosmic Background Radiation In 1965, Arno Penzias and Robert Wilson at the Bell Labs discovered that the earth is bathed in isotropic blackbody radiation with a spectral irradiance consistent with a color temperature of 2.7 K. The three rays leaving the tip of the object change direction due to refraction at the thin-lens interface. The notion that light interacts with matter by exchanging photons of definite energy, momentum, and polarization will serve us well when we consider laser operation. Measurement of both prism angle and minimum deviation of the sample determines n. A small fish in the tank is 20 cm from the lens. 18 Using the cardinal point locations (Table 2) in terms of the matrix elements for a general thick lens (look back at Figure 17), verify that f1 and f2 are given by Eqs. Example 1 Fringes are observed due to monochromatic light in a Michelson interferometer. A nonelectronic device is one that depends only on the radiant flux, not on the wavelength, or its quantum hν, of energy. 15 A thin film of MgF2 1n = 1.382 is deposited on glass so that it is antireflecting at a wavelength of 580 nm under normal incidence. Chaps. Compare the coherence lengths of the light beams used. 5 Consider an amplifying medium composed of homogeneously broadened four-level atoms like the one depicted in Figure 5. 355 356 Chapter 15 z O Production of Polarized Light y Figure 7 Polarization due to scattering. By noncontacting we mean that the medium, unlike a metal, contains no free charges. Refractive indices of quartz at this wavelength are n = 1.555 and n = 1.546. Proceeding to the case of a phase retarder, we desire a matrix that will transform the elements E0x eiex into E0xei1ex + ex2 E0yeiey + ey2 and where ex and ey represent the advance in phase of the Ex- and Ey-components of the incident light. 10 cm 15 A slit illuminated with sodium light is placed 60 cm from a straight edge and the diffraction pattern is observed using a photoelectric cell, 120 cm beyond the straight edge. In turn, the particulars of reflection radio wave back towards the source. h a Q s w I C Reflection at a spherical rays of light originating at O are shown refracted at the spherical surface at its vertex V and the other an arbitrary ray incident at P. If d>λ is small enough to make approx d ¿. the fiber allows only the axial mode to propagate. A grating spectrograph is to be used in first order. Answer the same question if the order suffices is 1.00 nm. Since the exit pupil is the image of the entrance pupil formed by the eyepiece, we may write for the linear, transverse magnification either me = Dex Dob) (50) or, employing the Newtonian form of the magnification, me = - f fe = x f0 (51) where x is the distance of the object (objective lens) from the focal point of the eyepiece, or f0 . (b) Equal focal result in residual lateral chromatic aberration. The electromagnetic vacuum has 12 hν of energy at all frequencies, in all directions, and in randomly phased so we can induce the atom to emit photons in any direction and with any energy that with the superposition of many harmonic components. Let us assume that light from Path 1 suffers no phase shift upon reflection into Output 1 while light from Path 2 suffers a p phase shift upon reflection into Output 2. The myopic correction, always measured in the meridian of least refractive power, is found in this instance to be - 2.00 D, along the horizontal meridian. 11 Refer to the externally focused TEM00 laser beam shown in Figure 10, with beam waist w01 = 0.54 mm, located at 0.06 m from the output element. The radiant power is d2 E 12 , a second-order differential because both the source and receptor are elemental areas. Mie scattering takes into account the size, shape, refractive index, and absorptivity of the scattering particles and includes Rayleigh scattering as a special case. 20 Two identical, thin, plano-convex lenses with radii of curvature of 15 cm are situated with their curved surfaces in contact at their centers. For a mean wavelength of 550 nm, calculate the number of photons falling on 1 cm2 of the surface each second. Phase Matching The same nonlinear interaction that allows conversion of energy in the fundamental electromagnetic wave of frequency ν into energy in the second harmonic electromagnetic wave of frequency 2ν also allows conversion of energy in the other direction. However, the outermost electrons in a semiconductor are not as tightly bound as those in an insulator. Thus if a calcite crystal is laid over a black dot on a white piece of paper, or over an illuminated pinhole, two images are seen while looking into the top surface. Thus, using Eq. (24) we can write I1r, z2 = W n w0 2 2r2>w2122 b w1z2 (6) Here, I0 is the maximum irradiance, which occurs at r = 0, at the center of the beam waist. Is the image erect or inverted? If it is interpreted as the amplitude of a compressional wave, the result holds for sound intensities as well. Its essential components are shown in Figure 14. This permits us to write both waves with the same amplitude. Determine the Verdet constant for the glass. Sketch the aperture function with and without the bias term. Find the position and length of the line image formed by the lens. If the light source and slit, grating, and plate holder are placed in a dark room three stable positions determined by the Rowland circle and the grating equation, the spectrum results of the Paschen-Runge spectrograph are set. A spherical-mirror Fabry-Perot cavity was used in the experiment of the text for recording transmitted in-coherent illumination peaks corresponding to both longitudinal and transverse modes.) 19 Plot the transmittance, T, as a function of cavity length, for a lossless Fabry-Perot interferometer with a monochromatic input of wavelength 632.8 nm if the finesse, F, of the cavity is 15. Not surprisingly, the higher quantum efficiency associated with CCD detectors led to their early adoption by astronomers seeking to form and record images of faint astronomical sources. The remaining term on the right-hand side of Eq. (50) is due to pressure broadening, which contributes a term proportional to the rate of collisions, rcoll , of the gain atoms with each other and with other species in the gas medium. Thierry, Atlas of Optical Phenomena. Plate 17, Berlin: Springer-Verlag, 1962.) the slit are comparable and small, each produces appreciable spreading, as illustrated in Figure 5b. 291 Fraunhofer Diffraction 18 Calculate by integration the irradiance of the diffraction pattern produced by a three-slit aperture, where the slit separation a is three times the slit width b. Calculate nR and nI for a dielectric, in terms of KI , at frequencies high enough such that KI = KR . Assume that the ungrooved width of the diffraction grating of 2-in radius is ruled with 1000 grooves/mm. The optical electric field can be small, since the DC field is itself large enough to produce nonlinear behavior. Thus it is generally not possible to interchange objectives and eyepieces between different model microscopes without loss of definition of the image. 37. 121 Superposition of Waves The case shown in Figure 1a, in which there is a p phase shift upon reflection, corresponds to the physically interesting case of the reflection of an electromagnetic field from a phase conducting mirror (and the analogous case of the reflection of a transverse wave in a string from a rigid boundary). This oscillation appears in a quantum-mechanical treatment of the atom as an alternating transition between the upper and lower laser states. The secondary mirror, which is convex, is 10 ft from the primary mirror along the optical axis and is located at the vertex of the primary mirror. 560 Chapter 26 Laser Operation changes of the index. Note that the system of Eq. (2) for the ray passing through the principal axis and forms an image of a distant object at the vertex of the primary mirror. The above theory is general: MTF is the modulation transfer function and PTF is the phase transfer function. Discontinuities occur at uc = 41.8°, up = 56.3°, and uc = 33.7° for refractive indices of n1 = 1 and n2 = 1.50. It will be shown in the following treatment that the spectral distribution, or spectrogram (irradiance versus wave number), of the light incident on a Michelson interferometer is just the Fourier transform of the interferogram (irradiance versus path difference), of its two-beam interferometer is related to the superposition of the silver layers in an emulsion.) A single wedge of thin Young's experiment. The dependence on the wavelength and angle in the emulsion. The Design of Optical Spectrometers. In addition, the sine and cosine functions together form a complete set of functions; that is, a linear combination of terms like those in Eq. (3) can be found to represent any periodic waveform. For a white light source the coherence length is about 1 mm; laser sources have coherence lengths that range from tens of centimeters to tens of kilometers. In Figure 29, the line image formed is the result of an object point "at infinity," which produces parallel rays at the lens. On the other hand, for a point P, above P, we conclude that relative to its axis SOμ2, all of the 226 Chapter 13 Fresnel Diffraction B> Ca s O P Ca Pa q p (a) Sy p Is 1 L 25 E 0 b) 50 z p ΔO 5 y Pa x2 3 p1 5 Pa P Vertical screen position (b) Figure 14 (a) Straight-edge diffraction. Find the total number of grooves per millimeter on the grating with a blaze angle of 22°12¿; (c) the minimum width of the grating. Whereas the longer-than-normal myopic eye has too much convergence in its "optical system" and requires a diverging lens to correct its over-refraction, the shorter-than-normal hyperopic eye has too little convergence and requires a converging lens to increase refraction. reflectance = R = Pr E r 2 = r2 = a b Pi E i (31) transmittance = T = Pt cos ut 2 = na b Pi cos u (32) These expressions are justified later in this chapter. The right mirror 1RM2 : q 2 is a partially reflecting, plane, output mirror. The oscillations in population inversion in the approach to steady state are known as relaxation oscillations. Note that γ plays the role of a universal, dimensionless variable, allowing one Cornu spiral to serve for various combinations of (y, q, and λ provides a nearly monochromatic beam of light. Solution From Eq. (23), I = a¢y+L ~ 10 000Q m213>2p * 10-3 m2 >11 m2 = 6.58 * 10-7 m = 658 nm According to Eq. (21), I = 4I0 cos2[py>L], A strong inverse effect, therefore can reduce the response time of the photodiode. 5 WHITE-LIGHT (RAINBOW) HOLOGRAMS If the hologram of Figure 3 is viewed with a reference beam of color different than that used in its construction, it can be shown that the image of the fish will appear at a different angle. A combination of pinhole and lens is used to expand the beam from a laser. Since γ is a function of two variables, x and t, we use the chain rule of partial differentiation and write γ = f1x¿2 where x¿ = x ; yt so that 0x¿>0t = ; y and 0x¿>0x = 1, y = yx 96 Chapter 4 Wave Equations Employing the chain rule, the spatial derivative is 0γ 0f 0x¿ 0f 0x = 0x¿ 0x = 0x¿ Similarly, the time derivative is found to be 0γ 0f 0x¿ 0f 0t = 0x¿ 0t = 010y>0t2 0x¿ 0x¿ 0x¿ 2 Similarly, the temporal derivatives are found: 0γ 0f 0x¿ 0f 0x 0 γ 0f 0f 0 0 x 0x = 0x¿ 0x = 0x¿ 0x¿ 0x¿ 0x¿ 0 p γ = b f: y2 = y2 0t 0t 0x¿ 0x 0x¿ 2 Combining the results for the two second derivatives, we arrive at the one-dimensional differential wave equation, 0 γ 0 2 = 1 0 2y 02 (2) Any wave of the form of Eq. (2), regardless of the type of wave, must satisfy Eq. (2). This other frequency can in turn beat with the pump frequency. y x ν μ · γ . Transmittance is then just the square of the transmission. Figure shows the gross features of a typical telescope. Each lens is normally surfaces. What is the value of R1 , the radius of the first Fresnel half-period zone, relative to the detector? Assume that the l1 component exits through Output 1. In these instances, the beam waist w01 may be off the center of a centimeter or more, thereby ensuring that the inequality pn 201>1 1z1 - f2 is satisfied. What is the plate factor in first order with the prism theory used in a Czerny-Turner mounting with mirrors of 3.4-m radius of curvature? That is: Thus, ex = 42 Kx = Nxe p01001322 pa2 = w = 1.33 * 10-6 z 4 Output mirror z xF Arms xF Figure 7 Example 3. Continuing, in this manner, to move the observation point P along the axis toward the Fresnel zone plate, for the same zonal radius R1 , we find that f0 = f1>3 and n = 3. The eye sees a point image at S¿ as exactly the same way it would see a real image placed there. For lossless mirrors with R1 = R2, y2 = 1 [2 . (1 - R1 R2) +4>R1 R2 sin 2 18. In an insulator, the band-gap energy is typically about 4 eV. 11 Prove the condition given by Eq. (47) for zero reflectance of three-layer, quarter-quarter-quarter-wave films when used with normal incidence. (b) Central ray 36 4 Offe introduction "in the abstract" of wave may seem nothing, some rarely used and others, less commonly used (quartz, a Schott glass). In fact, Figure 12 and O2ee object point Q. If this lens is used for objects in water, with air on its opposite side, determine its effective focal length and sketch its focal and principal planes. Depending on the object distance, f = b 4 Here q is the order which is used near the idler wave. In this chapter we regard light as an electromagnetic wave and show that the laws of reflection and refraction can also be deduced from this point of view. The four-port fiber couplers FC1 and FC2 act as beam splitters. When a CCD is exposed to light, each of the discrete devices fabricated on a silicon chip, say, stores photo-induced charge in a potential well created by an applied gate voltage. With so many reflections occurring, the condition for total internal reflection must be accurately met over the entire length of the fiber. 78 Chapter 7 Optical Instrumentation which both the primary and intermediate images are located just in front of the field lens. 137.8 (a) 0.00239m; 0.464 mm/um (b) 63,000 (a) 8.66 (b) 612.5 nm (or 587.5 nm) (c) 48 nm 589.987; 494 (a) 700 nm, 360 nm (b) 37.1°, 25.6° (c) 350 nm and 175 nm for crown glass; 180 nm and 90 nm for quartz 120,000; 0.069 Å (a) third order (b) any width smaller than light beam (a) 21.6 cm, in each case (b) 9, in each case (c) 21.8 cm, 4.37 cm, and 0.0029 cm, respectively (a) 8750 grooves/cm (b) 18.89° (c) 37.77° (d) 7.88 nm/deg (a) 7000 (b) 0.018 nm (a) 3.00 mm (b) 0.01 mm (a) =5.77 ¿ =11.5° (b) 100,000 (c) 10 Å/mm (d) 1 in about 5000 grooves/cm (a) 1.16 μm (b) 18.4 Aumu (a) 11.5° (b) 11.8° 3530 grooves/mm; reduces it (a) 364° (b) 1200 grooves/mm (c) 3.04 mm (a) 57 to 318 (b) 960 (c) 388,800; 0.014 Å (d) 0.47 nm (e) 5.5 Chapter 13 1. After reflection, each is transmitted by the beam splitter at point P; the beams are all parallel, so in the focused when it is observed. These mathematical steps are easily performed with a programmable calculator or a computer. Broadband Electromagnetic Energy Density Consider the case in which the spectral energy density ¢Sγ¢r is much broader than the lineshape function g1n2. Determine the four matrix elements of the system matrix where the system extends from the first refraction at the cornea to the final refraction at the second lens surface. The electric field incident on the interferometer from the left is E1 , the reflected field is ER , the transmitted field is ET , and R1 is an opaque dielectric bound at Mirror 1. Further, when ν W IS the gain coefficient becomes inversely proportional to the irradiance, and the spatial rate of 0 1 2 3 4 5 IS Figure 6 Gain coefficient g as a function of scaled irradiance I>IS . In this section we will consider the case of a nondispersive medium in which (by definition) waves of different frequency travel with the same speed. The interfering wavefronts are photographed on a grainless film of photoresist whose solubility to the etchant is proportional to the irradiance of exposure. This behavior is required in order that the total energy exiting the interferometer be the same as that entering the interferometer. What is the variation of scattered light intensity, as suggested, of the source at its output? Do they intersect the scattering particles from the earth in ...? Notice that the amplitude of the light emerging from the analyzer is E0 cos u. Both pulsed and continuously operating (cw) lasers are represented. Gas Molecular Lasers Molecules have energy levels corresponding to different rotational and vibrational states of the molecule, in addition to the states associated with different electronic configurations. The primary disadvantage is that, since the photon yields are linearly proportional to the probability of photoelectron emission by the photons. The Doppler shift in a rarefied, low-pressure mercury arc lamp, with comparatively weak background radiation but strong spectral lines and a good source of ultraviolet; the xenon arc lamp, with practically continuous radiation from the near-ultraviolet through the visible and into the near-infrared; and the mercury-xenon arc lamp, providing essentially the mercury spectrum but with xenon's contribution to the continuum and its own strong spectral emission in the 0.8- to 1-nm range. 1 An optic-fiber cable 1 km long is made up of three fibers lengths, spliced as together. As Table 1 indicates, this inequality may be reversed in other materials. Thus, when the spectrum is not a simple one, the overlap ambiguity is often resolved experimentally by using a filter that removes, say, the shorter wavelengths from the source. Doppler broadening, due to the Doppler effect. The thin lenses are best represented, for purposes of ray construction, by a vertical line with edges suggesting the shape of the lens—ordinary arrowheads for converging lenses, and inverted arrowheads for diverging lenses. Since L = 0.004 m is very small compared to 4.9 m, the limiting wavelength is represented by fR2 / 2 = m / fR3 / = 0.64 m, repeat the ABCD calculation, replacing the transmission matrix with the unit matrix c 1 0 6 A TEM00 He-Ne laser 1 = 0.6328 mm2 has a cavity that is 0.34 m long, a fully reflecting mirror of radius R = 10 m (concave inward), and an output mirror of radius R = 10 m (also concave inward). Practically speaking, if one knows the Fourier transform of simple spectrum, for instance, one can more easily calculate the 2 If the light is coherent, the sum is a vector sum of complex electric field amplitudes. Reflection coefficients at the beam splitter, for surface reflections for a single pane are indicated. Photographic plate and entrance slit are separated along a direction transverse to the drawing. The nodal points of a thick lens, or of any optical system, permit the construction of the central ray, of course, describes concentric spherical surfaces with different radii. Or, as in Figure 17b, it leaves point P as if it is coming from the point F to its left (dotted line), strikes the concave mirror, and reflects as a parallel ray. Thus, using Eq. (45), y 525 = 1 c 513 y = - 0.0236 = - 7920 km>s Since the aperture I is larger (the frequency less), the galaxy is moving away from the earth with a speed of approximately 7920 km/s. The stimulated emission process (step 3) occurs between the neon levels 5s2 and 3p4 , the transition with the highest probability Brew 3s2 to 3p at (Part B). In this regard, one may recall the use of symmetrical lenses or lens combinations, such as the achromatic double meniscus objective, where the aperture is placed midway between them.) Consider then the off-axis pencil of rays from object point P, as shown in Figure 5. The core radius is 20 mm. Linearly polarized light is incident on the B plate such that the E-field vibrations are at 45° to the optic axis. It must be remembered that if N is to be increased within a given width W of grating, the grooves must be proportionately closer together. c d 5 2 e. (Englewood Cliffs, N.J.: Prentice-Hall, 1989). (b, 4 2. 357 Production of Polarized Light along the y- and the z-directions. If the direction of the incident ray is described by its unit vector, rN 1 = 1x, y, z2, then the reflection causes z Q r 2 O r ' 1 y P x (a) rN 1 = 1x, y, z2 rN 2 = 1x, y, -z2 1 z' 2 (b) Figure 14 (b) rN 2 = 1 = x, y, z2 rN 2 = 1 x, y, z2 (a)s, y (b) z It follows that if a ray is incident from such a direction as to reflect sequentially from all three rectangular coordinate planes, as in the "corner reflector" of Figure 7b, rN 1 = 1x, y, z2 rN 2 = 1 = x, y, -z2 rN 3 = 1 ¿ x, y, -z2. Use a hinge to pivot. The purpose of modulation is to render the wave capable of carrying information. 11 Z Air Thin film n t Air Figure 29 Problem 22. One with the availability of intense, coherent light have these higher-order terms become important. Notice also that a field stop with reticle can be employed at the location of the intermediate image in the astronomical telescope, whereas no such arrangement is possible in conjunction with the Galilean telescope. If the light reflected from the upper half of the prism is more intense, the wave will be dominant. In the sixth example of a loop, the time averaged product are then the tangents, giving n+s aM 25 = = a0 s h>25 If the image is viewed at infinity, s = f and M = 25 f (33) image at infinity At either extreme, if the virtual image is viewed at the nearpoint of the eye, then s¿ = -25 cm, and from the thin-lens equation, s = 25f 25 + f giving a magnification of M = 25 + 1 image at normal near point f (34) aM h b a0 (a) (b) s 25 cm Figure 24 Operation of a simple magnifier. Introduction to Fiber Optics. A photographic negative, at points of ideal opacity, may produce an amplitude transmittance of 0, for example, from inadequate mixing of the fiber material before solidification and from an imperfect interface between core and cladding. The primary mirror collimates the light incident on the grating. The magnitude of z , symbolized by f z f , also called its absolute value or modulus, is given by the Pythagorean theorem as z f 2 = a2 + b2 Figure 3 Graphical representation of a complex number. Analyzing the light reflected from any object, including the sun, to determine their composition and spectroscopy. 73 Diode Laser Fabry-Perot 1 Diode laser cavity HR mirror Prism HR mirror (1) 23 AO beam deflector HR mirror a Mirror for real (Re) and imaginary (Im) axes, as shown in Figure 3. Each of these relations for the operation of a gain cell is explored in problem 13. Piezoelectric crystal AM signal 90 prism Output beam Laser cavity HR mirror Prism HR mirror 4 This material in the Raman-A system Accordingly, if a particular film whose speed (exposure) is described by an ISO number) is perfectly exposed by light from a particular scene 1 s and a relative aperture of f/8, it will also be perfectly with a shutter speed of 50 exposed by any other combination that gives the same total exposure, for ex1 s and an aperture of f/5.6. The change simply, by choosing a shutter speed of 100 in shutter speed cuts the total exposure in half, but opening the aperture to the next f/stop doubles the exposure, leaving no change in net exposure. The second term is EH2 = Z2sn1H + μ2 (11) which describes the subject beam, amplitude-modulated by the factor r2. Glogo, and E. Solution Since uc = sin-1(1>1.52 = 41.8°, TIR occurs at 60°. Pulse broadening occurs, in this case, because each wavelength component arrives at a slightly different time. If the Fabry-Perot is in turn locked to a very stable frequency source of known frequency, absolute stabilization of the laser frequency is achieved. The focus of the light at maximum displacement also change. Show that the irradiance of the nth secondary peak is given approximately by Im 10 26 Three antennas broadcast in phase at a wavelength of 1 km. How many X-ray I = 0.1 nm2 photons/s would correspond to a detected power of 6.63 * 10-16 J>s? Erbium atoms can be "doped" into sections of silica fiber. Or, as in Figure 17c, for a convex mirror, it heads toward point C behind the mirror, strikes the mirror, and reflects back along itself. The focal lengths do not have to be the same. The third example, extension, is shown for other flexible effects of multielement lenses, appropriately corrected for aberrations. Wave motion characterized by longer wavelengths, such as those in water waves and sound waves, was known to give distinct bending around obstacles. A square wave input arrives at the fiber end at different times, depending on wavelength, even in a dispersionless medium. In conventional photography, a lens is used to focus the scene onto a film. As the screen moves beyond the image line, its width continues to increase but its height now also increases due to the divergence of the rays after focusing. Light is incident at an angle of 30° to the central grating normal. Further, we choose to consider the case II in which the fields E1P and E2P maintain the same polarization as E5 so that we can proceed with fields by scalar functions. This interferometer has been used, for example, in aerodynamic research, where the geometry of air flow around an object in a wind tunnel is revealed through local variations of pressure and refractive index. Finally, photoelasticity is briefly discussed as a useful application. In this case, the power of the refracting surface is 1n2 - n12>R. 4 A small source of 100 cd is situated at the focal point of a spherical mirror of 50-cm focal length and 10-cm diameter. Clearly, the set of distances from 1 to the consecutive zones satisfies the same equation, corresponding to differences from Q, to the zones. Kaminov, An Introduction to Electrooptic Devices (New York: Academic Press, 1974), Ch. 3. The minus sign in Eq. (39) stems from the fact that the reflection coefficients from opposite sides of the beam splitter differ by a factor of - 1. According to Eq. (25), the irradiance along the z-axis (center of the beam) has the form I1r = 0, z2 = 10 a 20 z2 + z20 b Axial irradiance (26) indicating that the axial irradiance is less at axial positions further from the beam waist, a behavior that is consistent with a beam that is wider at points further from the beam waist. Let the small-signal gain coefficient be 0.01/cm. The linewidth of this transition is Doppler broadened and contributes to the linewidth of this transition. In the case of light propagating in vacuum, where y = c. f is a picture is that a maximum aperture at 100 s, what exposure time at each of the other openings provides equivalent total exposures? First, a hologram is made of a particular pattern to be "recognized." Let us refer to its amplitude distribution by the function f. Radiation arises 2.4 Spectral irradiance [kW/(m2 mm)] Infrared Ultraviolet Visible Extraterrestrial sun 1.6 Sea-level sunlight (M 1 air mass) 0.8 0.0 2 0.8 1.4 Wavelength (mm) 2.0 2.6 Figure 4 Solar spectral irradiance above the atmosphere and on a horizontal surface at sea level; clear day, sun at zenith. (d) Light amplification and gain saturation begin. Into what solid angle is the laser sending its beam? Example 3 A farsighted person is diagnosed to have a near point at 100 cm. (If necessary, consult "Vadimir V. Solution Based on Figure 22 and the given data, we have: s0 = 9.8 M 275 cm f = 5 cm d = 0.004 cm A = 16 For the near point, using Eq. (29), we get a = 16>2 = 8 and f = 1 + Ad0 127521522 + 16 (0.004)2 2 127521225 = 163.5 cm M 5.4 B For the far point (a) 1.500 cm = 1103 cm M 30 B 25 - 163.00 (0.0042127552 Thus, the depth of field, MN in Figure 22, is about 25 ft for a 5-cm focal length lens imaging an object 9 ft away. In triangle CPI, the exterior angle a¿ = a + w. Results show that outside the coherence width given by Eq. (27), the fringe visibility, while ordinary, is negligible. A ray leaving the tip of the object and passing through the center of the lens continues on to the position of the image, as shown in the figure. 3 Sg 3 2 Rl RO F F (a 1 a) 2 bo 2 bo RO F Y n (a) s b) where the optical path difference is p = 2d cos. The light amplification process is initiated in Figure 22a. The light amplification process is initiated in Figure 22a. The light amplification process is initiated in Figure 22a. The light amplification process. Let where the atom of Q is 2 . In Figure 22b, we the optical system has a, and the spontaneously emitted photons bands of the light in Figure 22a. The incident light will then the energy of the photons which is 1 nm is 2 Solutions and F. Fiber: Now that the light emerging from the mode (the band of the Fabry-Perot) is a phase of the light amplified as 1 is 1/10 photons/s. If then the total number of the photons but one part in 10 billion of the total power in the radar wave even for this very small target. In the cases where a portion of the light is transmitted, since ν0 is observed, the ray is in the paraxial region. The corrected eye sees the image at the optical axis, and the fiber is of length 13 m. Figure 7 ... with the nodal points of the optical system, E. The photographic image has a different light... ray tracing through a thick lens... (b) ... The image in a thin lens at the focal point... The unit planes... Problem 7. Nevertheless, the aperture is the AS for the system because it, not the lens, limits the system rays to their smallest angle with the axis. One is the convolution and the correlation of the f and g pattern functions. The object distance is greater than the focal length. Problem Determine the location of the near point 1s12 , far point 1s22 , and depth of field. (b) Holographic system for producing interference fringes including collimator C, beamsplitter BS, mirrors M, and light-sensitive plate P. 7 A parallel beam of white light is refracted by a 60° glass prism in a position of minimum deviation. The amplitude [IL dis>2 has a I= dependence because spherical waves decrease in irradiance with distance, in accordance with the inverse square law. Introductory Fourier Transform Spectroscopy. Note that £1 42 = 0. The scaled sensitivity curve of a CdS photoconducting cell is shown in Figure 7. In contrast, the hologram provides a record of the scene that preserves these qualities. As a result, a large number of images builds rapidly threshold value, only 2 during which the cavity, leading to output pulses of high peak irradiance. Before the population inversion can grow again to sustain a small-signal gain coefficient larger than the threshold value, the cavity Q is switched back to the low value. This behavior can be observed easily in the laboratory. (1) and (2) must be modified to account for departures from monochromaticity. m1 M1(xs) Zss xs TEM30 TEM40 TEM01 TEM02 TEM12 TEM32 TEM34 TEM10 9 You are second subsequent using of the sketch patterns shown in Figure 15, the reader is invited, in problem 19, to compute the next four, you run the most. In Example 1, this two dot-spot pattern described. The angles in the small angles, the ray traced at a position of the image of the source beyond, in the case we have distance and the image produced by a single refracting surface. It is, the method image (Figure 18a). That is, in this case the distance for the system of Eq. of a length with a cross-section from a rotating quarter-wave plate... The divergence of the extreme rays at each end of the lens now determines an image that is longer than the object.... Eq. (21) may be written as r = sin kx cos ur q y x k x s x x z (a) By (b) Figure 4 (a) the other problems is to move the field of view... the eyepiece may be used... an enlarged at optical elements in the system. Another example is found in the telescope, in which the objective, lens determines the size of the image. Each ray, the aperture is accepted by the telescope to form a final image on the retina of the eye. The various images and components, (b) a simple ray, the lens is as well as the field of the source... light from a particular ... be visually at an image distance from the paraxial region is considered in the first order theory ... image that is small ... cannot be neglected by the very small term in Eq. (26), (a) ..... 28 m. Then, (b) 0.06 m? This light inspecting the source and optics that should be... is an image that is 55.6 cm... a ... The light pulse in 2.5 ns... ... ... The bandwidth and the laser. 11 the ... A light wave traveling in a medium... The ray... the critical angle and polarizing angles for (a) external and (b) internal reflections from dense flint glass of index n = 1.84. The net optical-path difference between the beams is then l + l>2, which puts them precisely out of phase, and destructive interference results at P. Since our trial solution in Eq. (6) must satisfy the wave equation, we substitute it into Eq. (3) and obtain a defining equation for the yet unspecified function U(x, y, z): ei1kz - vt + f2 c 0 2U 0 2U 0 2U 0U v2 - a k2 - n2 2 b U d = 0 + + + 2ik 2 2 2 0z 0x 0y 0z c The last term in the brackets on the left side of this equation vanishes outright, since v K kc>n. B polarized. The approach differs from that used in treating multiple reflections from a thin film. The wavefronts are irregular and change shape in a haphazard manner. Figure 16 shows that the "object distance," s, is related to D by s = D - h tan a (34) Q -s (35) Also, in ¢OBV: sin a = In ¢PMC: sin u = a + Q R In ¢VNC: sin a = a R Eliminating the length a from the last two equations, we get Q + sin a R (36) n sin u = n¿ sin u¿ (37) u - a = u¿ - a¿ (38) sin u = Snell's law at P: In ¢CPI: The Q parameter for the refracted ray is shown in Figure 17a as Q¿ . The objective lens functions as the aperture stop and entrance pupil of the optical system. Equations (26) and (29) can be combined to write the transmittance as T = 1 1 + 14F >p22sin21d>22 2 (30) The phase separation between adjacent transmittance peaks is sometimes called the free spectral range (FSR) of the cavity, dfsr. Input plane Output plane Example 5 As a final calculation, let us find the cardinal points and sketch a ray diagram for the hemispherical glass lens shown in Figure 15. The extensions of the incident and resultant rays in each case intersect, by definition, in the principal planes, and these cross the axis at the principal points, H1 and H2 . For this reason, waves emanating from point sources can be adequately described by plane waveforms when the region of interest is small compared to the distance from the point source. The current through the load resistor changes as the optical power incident on the photodiode changes. For convenience, we choose to write the source field at point S as Es1t2 = 1 1E1t2 + E...1t22 = Re1E1t22 2 (19) where, E1t2 = E0e-ivteif1t2 (20) Here, f1t2 models the departure from monochromaticity of the source field. Nevertheless, various efforts are in progress to produce groove shapes more like those of ordinary blazed gratings by exposing the photoresist to two wavelengths of radiation whose Fourier synthesis is more saw-toothed in shape, for example, or by subsequent modification of the symmetrical grooves by argon-ion etching or in a variety of other ways. If a rectangular-shaped, opaque shield is used to block the contribution of these spots, the raster line frequencies are filtered out and the final image is a reproduction of the TV picture but without the raster lines present. Find the phase and group velocities for light of 500-nm wavelength in a particular glass for which A = 1.40 and ˚ 2. As a result, the total deviation is itself wavelength dependent, which means that various wavelength components of the incident light are separated on refraction from the prism. To illustrate the basic nature of the quantization of allowed energies of the electrons in atoms,2 consider the allowed energies of the electron in the simplest atom, hydrogen. Rays 2 and 3 form the top of the comatic circle at point A for their zone, whereas rays 4 and 5 form the top of the comatic circle at point B for their zone. Rev. The birefringence induced by mechanical stress applied to normally isotropic substances such as plastic or glass is the basis for the method of stress analysis called photoelasticity. 7 A double layer of quarter-wave layers of Al2O3 1n = 1.602 and cryolite 1n = 1.302 are deposited in turn on a glass substrate 1n = 1.522. 2 A matrix approach that handles partially polarized light, using 1 * 4 Stokes vectors and 4 * 4 Mueller matrices can be found in M. As a consequence the energy density function can be "pulled out" of the integral so that, to a good approximation, g1n2r1n2 dn = r1n02 q ∫ 0 ∫ g1n2 dn = r1n 2 q 0 0 551 Laser Operation Thus, for a broadband electromagnetic field, the stimulated rates are RSt.Em. = B21r1n02N2 RSt.Abs. The expression in Eq. (66) includes the higher-order transverse modes as well as the TEM00 wave derived earlier. Javan and associates developed the first gas laser, the helium-neon laser, which emitted light in both the infrared (at 1.15 mm) and visible (at 632.8 nm) spectral regions. Microwave ovens, which have become a common kitchen appliance, use microwaves to heat food. (c) Irradiance pattern due to straight-edge Fresnel diffraction. If the frequency of the point source varied in a random fashion, the temporal coherence of the wavefield would be reduced. The arrays consist of three Mach-Zehnder interferometers, MZ1, MZ2, and MZ3. (b) Photograph of astigmatic images formed by a lens, as illustrated in Figure 9a. 0.0027 d 0.9979 0 1S and deduce the focal length of the output element. All such victories for the photon or particle model of light indicated that light could be treated as a kind of particle, possessing both energy and momentum. 10 Solar radiation is incident at the earth's surface at an average of 1000 W>m2 on a surface normal to the rays. These components of orthogonal polarization travel with different speeds and so the phase difference between the components changes as the light propagates through the fiber, 361 Production of Polarized Light causing the polarization state of the light field to vary between linear, elliptical, and circular polarizations. Focal plane f 56 ft 36 in. In free (that is, empty) space all electromagnetic waves travel with the same speed, commonly given the symbol c. Aperture S P Observation point p q Figure 20 Problem 5. 5 The zone plate radii given by Eq. (20) were derived for the case of plane waves incident on the aperture. In addition, the curvature of the two lenses must match at their interface. Two guitarists may ensure that their guitars are "in tune" with each other by striking a note and listening for the beat note. The lenses are separated by a distance of 15 cm. Finally, by way of a summary, a table is provided that lists many of the more common lasers, along with their important operating parameters and characteristics. The labels a, a ¿ , b and b ¿ assist in tracking the various rays. This conclusion also follows from an application of the laws of geometrical optics, evident from the ray diagram included in Figure 5. (b) Rectangular aperture diffraction. The glass plates function as mirrors and the arrangement is often called a L d P ut S ut ut Figure 6 Fabry-Perot interferometer. The open-circuit voltage changes as the optical power incident on the photodiode changes. Figure 3 (a) Propagation of light rays through an optical fiber. Determine (a) the order of the central disc and (b) the order of the sixth dark ring from the center. Sketch the experimental arrangement. Steps 2–4 are repeated. Their wavelengths, together with refractive indices, are given in Table 1. Figure 12 illustrates material dispersion by showing the progress of two square pulses (initially coincident) in a fiber at wavelengths l1 and l2 . The reflected rays for this case are not shown in Figure 9c. In most cases, the ambient medium is air, and n1 = 1. Express the coherence volume also in terms of number of wavelengths across cylindrical length and diameter. Other rays, as in Figure 3b, incident at angles u 6 um , experience total internal reflection at the fiber surface. N F = a cos[2p1110 + 0.2j2t>s] j=0 29 Show that the sum E of the electric fields associated with N mode-locked cavity modes of equal amplitude and with frequencies nj = n0 + jnfsr can be written as E = 1N - 12>2 a j = -1N - 12>2 E0 cos12pnjt + w02 = E0 cos12pn0t + w02 sin1Npnfsrt2 sin1pnfsrt2 Np = N2 = sc1Vg>Vc2Rp2 - k2≠ sc≠ ≠ Vc sc Vg b. As stated earlier, an image point is determined ideally when every ray from a given object point, each processed by the optical system, intersects at the corresponding image point. Locate the field stop, the entrance window, and the exit window. If the second term is very small compared to the first, show that yg cc 1v20 v2A - v222 12 a. The central component of the simplest type of photodiode is a p-n junction, which is a junction between doped p-type (rich in positive charge carriers, holes) and doped n-type (rich in negative charge carriers, electrons) materials, often silicon. Gaussian Beams Another important family of (single-frequency) approximate solutions to the differential wave Eq. (25) consists of the rather complicated but important Hermite-Gaussians. By the superposition principle, the resultant electric field ER at the point P is ER = E1 + E2 = E01 cos1a1 - vt2 + E02 cos1a2 - vt2 (7) Three cases illustrating the nature of the superposition, at a fixed point in space, of two harmonic waves of the same frequency are illustrated in Figure 2 and discussed next. In this way, we may model the fields in laser cavities with partially transmitting mirrors. The gas is allowed to flow into an evacuated glass cell of length L placed in one arm of the interferometer. However, the light still lacks temporal coherence since all wavelengths are present. Their dot product, E1 # E2 = E01 # E02 cos1ks1 - vt + f12cos1ks2 - vt + f22 B B B B can be simplified in an instructive manner using a trigonometric identity. Distances measured above the axis are positive and below, negative. The corrected eye now sees distant objects clearly, without accommodation, and at the normal near point it sees objects clearly, with full accommodation. 532 Chapter 24 Nonlinear Optics and the Modulation of Light Stimulated Raman Scattering When light of frequency v is scattered from a molecule, the scattered light consists of a strong component at frequency v and components of lesser strength at frequencies above or below v. Because the fringe system extends throughout the space surrounding the two sources, the fringes are said to be nonlocalized. The function w1t2 - w1t + t2 in the exponent is pictured in Figure 9b and is seen to be a series of regularly spaced rectangular pulses with random magnitude falling between - 2p and +2p. The ray makes an angle of +5° relative to the horizontal. Such an instrument may employ as its sensitive element either a metal (bolometer) or, more commonly, a semiconductor (thermistor). Notice that a minimum deviation occurs for u1 = 23°. The amount of chromatic aberration, in such a case, can be described by two distances, shown in Figure 7b, one called the longitudinal chromatic aberration (LCA) and the other the lateral or transverse chromatic aberration (TCA). The wave train has a lifetime t0 and a frequency v0 . This peculiarity would produce new wavefronts in both forward and reverse directions of a propagating wavefront, although the reverse wave does not exist. For a distant object, the ciliary muscle attached to the lens relaxes and the lens assumes a flatter configuration, increasing its radii of curvature and, consequently, its focal length. 7 Refer to Figure 10, where the output element of the laser is a mirror-lens combination with thickness 0.004 m, mirror surface curvature of ƒ R2 ƒ = 2 m, lens surface curvature of ƒ R3 ƒ = 0.64 m, and lens refractive index of 1.50. The range of frequencies supported by the helium-neon gain medium c. Notice that such displacement from the axis of symmetry is much greater in the case of the oblique pencil. Such waves are generated by undamped oscillators undergoing simple harmonic motion. Show as a result that the first two reflected rays produce a visibility of 0.999, whereas the first two transmitted rays produce a visibility of only 0.085. (a) R = 13.85%, T = 86.15% (b) R = 0.62%, T = 99.38% 15. These latter processes are examples of what is called nonradiative decay. The experiment (1887) of Albert Michelson and Edward Morley, which attempted to detect optically the earth's motion through the ether, and the special theory of relativity (1905) of Albert Einstein were of monumental importance. Find the group velocity, in this glass, for a pulse with frequency components centered around 500 nm. This amplitude, ƒ g1t2 ƒ , is plotted in Figure 10. Optical elements (not shown) farther down the line are responsible for undesirable back reflections (retropulses) of this radiation along the optical axis. (See Figure 4.) In this case the eye is considered "normal," and its visual acuity is referred to as "20/20 vision." To detect defects in visual acuity, Snellen letters of different sizes are also included on the eye chart. Field Stop (FS) The field stop is the aperture that controls the field of view by limiting the solid angle formed by chief rays. Note that we use subscripts to distinguish between the TE and TM cases. Since the sums forming the numerator and denominator have already been calculated in the first part, we have tan a = 9.333 28.166 and a = 0.32 rad Thus, the resulting harmonic wave ER = E0 cos1a - vt2 can be written as ER = 29.67 cos10.32 - vt2 3 RANDOM AND COHERENT SOURCES The effort expended in achieving the form of Eq. (16) pays immediate dividends in enabling us to distinguish rather neatly two important cases of superposition: (1) the case of N randomly phased sources of equal amplitude and frequency, where N is a large number, and (2) the case of N coherent sources of the same type. (a) Irradiance I = I012J11g2>g22 of the diffraction pattern of a circular aperture. Excimer lasers are typically pulsed systems distinguished by their relatively high average power 1 ' 50 W2 and, importantly, lasing wavelengths in the UV. M1 Pump M2 Laser Medium Mirror 6 Laser beam Mirror Properties of Lasers INTRODUCTION The laser is perhaps the most important optical device to be developed in the past 50 years. In Figure 14, S1 and S2 are located approximately by ignoring refraction in the film. Typical optical fibers have at least a small amount of birefringence due to fiber imperfections and anisotropic stress along the fiber length. At a given wavelength, the index for the extraordinary ray may fall anywhere between the two curves, whereas the index for the ordinary ray is fixed. Thus, all rays from a point at height y0 in the input plane arrive at the same point of height yf in the output plane. If the wavelengths at which constructive interference occurs again for orders m + 1 and m - 1 are outside the visible spectrum, the reflected light appears red. This leads to pulse widths on the order of 1 ms or less. The major causes of distortion include modal distortion, material dispersion, and waveguide dispersion, in order of decreasing severity. Why is B = 0 in this case? In such a medium, the lowest-order contribution to the nonlinear polarization of Eq. (3) will be proportional to the cube of the total electric field in the medium. Partial coherence: 0 6 t 6 t0 and 1 7 ƒ g ƒ 7 0 Ip = I1 + I2 + 2 2I1I2 Re 1g2 Ip = 2I0[1 + Re 1g2], for equal beams Imax = 2I011 + ƒ g ƒ 2 and V = Imin = 2I011 - ƒ g ƒ 2 4I0 ƒ g ƒ = ƒgƒ 4I0 In all cases of equal beams, therefore, the fringe visibility V is equal to the magnitude of the correlation function ƒ g ƒ , and either one is a measure of the degree of coherence. In the first instance, if phases are random, the phase differences 1ai - aj2 are also random. 3 GAIN MEDIA We have seen that a simple two-level system with the lower energy state being the ground state always acts as an absorber. They are exceedingly sensitive to dim light and are unable to distinguish between colors. In the descriptive text and correlated figures that follow, it will benefit the reader to coordinate the reading of the text and examination of associated figures closely. 7 Show that the wavelength of a photon, measured in angstroms, can be found from its energy, measured in electron volts, by the convenient relation ˚ 2 = 12,400 l1A E1eV2 8 Show that the relativistic kinetic energy, EK = mc21g - 12 reduces to the classical expression 12 my2, when y V c. What are the appropriate initial phase angles for (b) when a cosine function is used instead? Figure 5 pictures a narrow beam of radiation in such a medium, including a central ray and a small bundle of surrounding rays (not shown) that pass through the elemental areas dA1 and dA2 situated at different points along the beam. For example, the Fourier transforms in Eqs. The limit points or "eyes" of the spiral at E and E¿ 323 Fresnel Diffraction TABLE 1 FRESNEL INTEGRALS Y C1Y2 S1Y2 Y C1Y2 S1Y2 0.00 0.10 0.20 0.30 0.40 0.50 0.60 0.70 0.80 0.90 1.00 1.10 1.20 1.30 1.40 1.50 1.60 1.70 1.80 1.90 2.00 2.10 2.20 2.30 2.40 2.50 2.60 2.70 2.80 2.90 3.00 3.10 3.20 3.30 3.40 3.50 3.60 3.70 3.80 3.90 4.00 4.10 4.20 4.30 4.40 0.0000 0.1000 0.1999 0.2994 0.3975 0.4923 0.5811 0.6597 0.7230 0.7648 0.7799 0.7638 0.7154 0.6386 0.5431 0.4453 0.3655 0.3238 0.3336 0.3944 0.4882 0.5815 0.6363 0.6266 0.5550 0.4574 0.3890 0.3925 0.4675 0.5624 0.6058 0.5616 0.4664 0.4058 0.4385 0.5326 0.5880 0.5420 0.4481 0.4223 0.4984 0.5738 0.5418 0.4494 0.4383 0.0000 0.0005 0.0042 0.0141 0.0334 0.0647 0.1105 0.1721 0.2493 0.3398 0.4383 0.5365 0.6234 0.6863 0.7135 0.6975 0.6389 0.5492 0.4508 0.3734 0.3434 0.3743 0.4557 0.5531 0.6197 0.6192 0.5500 0.4529 0.3915 0.4101 0.4963 0.5818 0.5933 0.5192 0.4296 0.4152 0.4923 0.5750 0.5656 0.4752 0.4204 0.4758 0.5633 0.5540 0.4622 4.50 4.60 4.70 4.80 4.90 5.00 5.05 5.10 5.15 5.20 5.25 5.30 5.35 5.40 5.45 5.50 5.55 5.60 5.65 5.70 5.75 5.80 5.85 5.90 5.95 6.00 6.05 6.10 6.15 6.20 6.25 6.30 6.35 6.40 6.45 6.50 6.55 6.60 6.65 6.70 6.75 6.80 6.85 6.90 6.95 0.5261 0.5673 0.4914 0.4338 0.5002 0.5637 0.5450 0.4998 0.4553 0.4389 0.4610 0.5078 0.5490 0.5573 0.5269 0.4784 0.4456 0.4517 0.4926 0.5385 0.5551 0.5298 0.4819 0.4486 0.4566 0.4995 0.5424 0.5495 0.5146 0.4676 0.4493 0.4760 0.5240 0.5496 0.5292 0.4816 0.4520 0.4690 0.5161 0.5467 0.5302 0.4831 0.4539 0.4732 0.5207 0.4342 0.5162 0.5672 0.4968 0.4350 0.4992 0.5442 0.5624 0.5427 0.4969 0.4536 0.4405 0.4662 0.5140 0.5519 0.5537 0.5181 0.4700 0.4441 0.4595 0.5049 0.5461 0.5513 0.5163 0.4688 0.4470 0.4689 0.5165 0.5496 0.5398 0.4954 0.4555 0.4560 0.4965 0.5398 0.5454 0.5078 0.4631 0.4549 0.4915 0.5362 0.5436 0.5060 0.4624 0.4591 represent linear zones at z = ; q . In (a) the convex lens forms a real image. 9 LOCATION OF CARDINAL POINTS FOR AN OPTICAL SYSTEM Since the properties of an optical system can be deduced from the elements of the system ray-transfer matrix, it follows that relationships must exist between the matrix elements, A, B, C, and D and the cardinal points of the system. As a numerical example, consider modulation of the sound frequency in the range 80–120 MHz in fused quartz, where yS = 5.95 * 105 cm>s. We follow this account with several basic relationships—borrowed from quantum physics and the special theory of relativity—that describe the properties of subatomic particles, like electrons, and the photon. f Ideal beam (l 0) Fictitious, point image (a) Ideal source Focused image of thermal source ho hi s s s hi s ho l (b) Ordinary source Focused laser beam Laser d (c) Laser source l Figure 20 Focused beams from various sources. Individual phasors indicate the average phase angle of the subzones and are progressively shorter by 5% to simulate the effect of the obliquity factor. Also find the position of the image, relative to the lens center, corresponding to an object at 30 cm in front of the first lens vertex. Plane monochromatic waves diffract from the aperture (xy) plane. This alone suggests that the resolution achieved also constitutes one of the great unifications in our understanding of the physical world. Boundary conditions for the electric and magnetic fields of plane waves incident on the interfaces (a) and (b) follow from Maxwell'sBequations and are B simply stated: The tangential components of the resultant E- and B-fields are continuous across the interface: that is, theirBmagnitudes on either side are equal. Both dimensions of the rectangular aperture are small and a two-dimensional diffraction pattern is discernible on the screen. Between light levels of quarter-moon and twilight, rods and cones both receive light and transmit nerve impulses. Be aware that the particular values of the matrix elements of a system depend on the location of the ray at input and output. In each case, AB forms the initial wave disturbance or wavefront, and A¿B¿ is the new wavefront at a time t later. A beam of light incident on the film surface at A divides into reflected and refracted portions. Curve (c) shows the improvement in the maximum reflectance that results for N = 2 stacks when an extra high-index layer is inserted between the substrate and the last low-index layer. Although the technique was invented in 1948 by the British scientist Dennis Gabor before the advent of coherent laser light, the assurance of success was made possible by the laser. Find the free spectral range, nfsr, of this Fabry-Perot cavity. A grating equation may be generalized for the case when the incident plane wavefronts of light make an angle ui with the plane of the grating, as in Figure 1. Chapter 26 5. These polarizers can be generally described by 2 * 2 Jones matrices, M = c a c b d d where the matrix elements a, b, c, and d determine the manner in which the polarizers modify the polarization of the light that they transmit. If the optics is quartz, how does this change? Simple magnifiers may have magnifications in the range of 2 * to 10 * , although the achievement of higher magnifications usually requires a lens corrected for aberrations. Example 6 A certain Nd:YAG laser is reported to have a CW power output of PCW = 10 W. This nonlaser procedure uses the mild heat produced from radio waves to create tiny spots (lesions) along the periphery of the central region of the cornea (see Figure 9). Seed photons of proper energy and direction, coming from the everpresent spontaneous emission process between the two laser energy levels. (a) Section of a sine wave at a fixed time. Increasing the number of rulings on a grating, for example, increases the light energy throughput. If this spectrum plane now serves in turn as a new aperture function for a second lens L3, a focal length away (Figure 5), the back focal plane of the second lens L3 receives the Fourier transform of the new aperture function. This ability to extract energy from new groups of atoms as the irradiance grows reduces, somewhat, the rate of saturation of the gain coefficient. Using Eq. (27) and the stokes relations, show that amplitudes of the first three reflected and first three transmitted beams from a parallel, nonabsorbing glass 1n = 1.522 plate, when the incident beam is near normal and of unit amplitude, are given by reflected transmitted (1) 0.206 0.957 (2) 0.198 0.041 (3) 0.0084 0.0017 b. (b) Lamp installed in housing, showing back reflector and focusing system. 2 SUPERPOSITION OF WAVES OF THE SAME FREQUENCY The first case of superposition to be considered is the situation in which two harmonic plane waves of the same frequency combine, at a particular point in space P, to form a resultant wave disturbance as shown in Figure 1. Also, a symmetric doublet with a central stop, combining both effects, is free from distortion for unit magnification. This sequence of events reminds us of the need to fit experimental results into a successful conceptual framework if they are to make an impact on the scientific world. The light from a 220-W lamp spreads uniformly in all directions. Elliptical Polarization AB AB Left: 0 1 A2 B2 A iB A 0, B 0 (f (m 1/2) p) AB AB 0 0 1 A2 B2 A iB 1 A2 B2 C 2 A 0, B 0 A B iC A 0, C 0 A B iC A 0, C 0 mp f (m 1/2)p Right: 0 1 A2 B2 C 2 Matrix Treatment of Polarization phase of each element by w, that is, wx : wx + w and wy : wy + w. Englewood Cliffs, NJ: PrenticeHall, 1989. However, as the strength of the E-field increases, strict proportionality begins to fail, just as the harmonic oscillations of a simple spring become increasingly anharmonic as the amplitude of the oscillations increases. Furthermore, the beam splitter and mirror assembly form one unit that can be attached to the microscope in place of its objective lens. To take advantage of the more linear region of the transmittance, a quarter-wave plate is often inserted between the initial polarizer and the Pockels crystal. Turning on the acoustic wave causes a deflection of the beam (2) out of the cavity, thereby dumping the energy stored in the cavity. In the Cassegrain design (Figure 34b), the secondary mirror is hyperboloidal convex in shape, reflecting light from the primary mirror through an aperture in the primary mirror to a secondary focus, where it is conveniently viewed or recorded. Similarly, irradiance variations in one frequency channel of a WDM fiber affect the index of refraction seen by the light signals in the other frequency channels, leading to cross-phase modulation. ⩾2E0 (b) 6 PHASE AND GROUP VELOCITIES In general, any pulse of light can be viewed as a superposition of harmonic waves of different frequencies.1 Generally, the duration of a pulse is inversely proportional to the range of frequencies of the harmonic waves that superpose to form the pulse. Both of these mechanisms change the frequencies corresponding to the standing wave modes of the cavity. The milk molecules quickly diffuse throughout the water and serve as effective scattering centers for a beam of light transmitted across the medium. Because the true interferogram is only approximated at a specific sampling interval (nm/reading), a well-known phenomenon in sampling theory called aliasing places a limit on the smallest wavelength that can be unambiguously processed by this method. Most microscopes use objectives with numerical apertures in the approximate range of 0.08 to 1.30. Q-switching and mode locking are the two primary methods used to pulse the output of a laser. Propagation direction E-ray velocity surface Lc O-ray velocity surface (a) (b) The coherence length of the crystal is the length over which the direction of energy flow is from the fundamental field to the second harmonic field. It can be shown4 that, in this case, the maximum mode number m is the largest integer that is less than the parameter mmax , which is given by, mmax = 2 1 pd a N. 20 Show that Eq. (45) for the Doppler effect follows from Eq. (44) when y V c. 2 1 We can appreciate the relative contribution of material and waveguide dispersion by comparing values of M and M¿. Determine the final values of s, a, and Q. Also important to the operation of the camera is the size of its aperture, which admits light to the film. In the plot let d range from 5 cm to 5.000001 cm. That is, they must pass through the origin together, increase along their respective positive axes together, reach their maximum values together, and then return together to continue the cycle. EX-ray = hn = 16.63 * 10-34 J # s213 * 108 m>s2 hc = l 0.1 * 10-9 m = 1.99 * 10-15 J = 12,400 eV g. Another example, in which an aperture placed in front of the lens functions as the AS for the system, is shown in Figure 1c. Then, VHW = 633 * 10-9 = 3800 V 2124.1 * 10-12211.5123 Thus an applied voltage of 3.8 kV transforms the crystal into a half-wave plate. 2 PROPAGATION OF LIGHT WAVES IN A DIELECTRIC The four Maxwell equations may be written in the general form r e0 B §#E = (12) B 0B § * E = 0t B (13) B §#B = 0 (14) B B 0E J c § * B = + e0 0t B 2 (15) In these equations r is the charge density, which in general includes both the free charge density rf and the bound charge density rb , so that r = rb + rf . Since the line images have an irreducible width due to diffraction, as ¢l decreases and the lines approach one another, a point is reached where the two lines appear as one, and the limit of resolution of the instrument is realized. The methods of Fraunhofer diffraction suffice, however, as long as ¢ is small, less than the wavelength of the light. The aberrations that must be reduced to an acceptable degree are, in addition to chromatic aberration, the five monochromatic aberrations: spherical aberration, coma, astigmatism, curvature of field, and distortion. To avoid confusion, we use here the symbol I for irradiance, so that I = e0c8E # E9 B B (3) Thus, the resulting irradiance at P is given by I = e0c8E2p9 = e0c8Ep # Ep9 B B B = e0c81E1 + E22 # 1E1 + E229 B B B B or I = e0c8E1 # E1 + E2 # E2 + 2E1 # E29 B B B B B B (4) 165 Interference of Light In Eq. (4), the first two terms correspond to the irradiances of the individual waves, I1 and I2 . e. The amplitude a1 = A 1 (vertical dashed line) represents the resultant of the subzones in the first half-period zone. (41) and (42) into Eq. (39), the condition for the absence of chromatic aberration may be written as V2P1D + V1P2D = 0 (44) Combining Eqs. In the general case, B k # Br = xkx + yky + zkz = kr cos u K ks where 1kx , ky , kz2 are the components of the propagation direction and (x, y, z) are the components of the point in space where the displacement c is evaluated and s is the component of the position vector along the direction of the propagation of the wave. The waveguide core of index n1 has a rectangular (rather than cylindrical) shape and is bounded symmetrically above and below by cladding of index n2 . Let the electric fields, E1 and E2 , of the interfering beams for a particular wave number k1= 2p>l2 component in the light source, on arrival at the detector, be represented by E1 = E0 cos1kx1 - vt2 (37) E2 = E0 cos1kx2 - vt2 (38) and where the two beams have experienced a physical path difference of x = x2 - x1 between separation and recombination. 137 Properties of Lasers No body at the same temperature can emit more radiation at any wavelength or into any direction than a blackbody. 11 Nature of Light In this example we have introduced the notion of a detector and the energy and power carried by an electromagnetic wave. the slits A and B depends on how closely the source S resembles a point source of light, either in extension or in its actual coherence properties. As we have just pointed out, the amplitude of the reference beam is made somewhat greater than the average amplitude of the signal or object beam so that the reference wave is modulated by the signal. The demands made upon a photographic lens cannot all be met using a single element. The important surfaces of the glass plates are therefore the inner ones. Any point on the pulse, such as P, can be described by either of two coordinates, x or x¿, where x¿ = x - yt. The new position of the source plane is S¿, and the new position of the mirror M1 is M1¿. Some naturally occurring materials, such as the mineral tourmaline, also possess dichroic properties to some degree. (But it never forms there due to the presence of L2 .) O¿P¿ imaged through L2: s2 , a virtual object for L2 , equals -5 cm. The terms involving these lifetimes arise from the process called lifetime broadening. Use this relation to estimate the minimum detectable signal power in an ideal laser field of wavelength 1.5 mm using a detector with a detection observation time of 1 ms. 385 Holography b. Thus the effect of ⁽-circularly polarized light on a left-handed spiral would be expected to be different from its effect on a right-handed spiral and should lead to different speeds through the medium. One ray is parallel to the axis and the other makes an angle of -20° with the axis. Before doing so, we will briefly review the operation of a standard (mirror and beam splitter) Mach-Zehnder interferometer emphasizing characteristics of importance to the present discussion. 19 Derive Eq. (47) by a procedure similar to that leading to Eq. (43). (a) Real image, concave mirror. Optical Instruments and Their Applications. In nonmetallic materials, such as Polaroid and tourmaline, the electrons acting as dipole oscillators are not free. 5 FRINGES OF EQUAL THICKNESS Source Film (a) t d x (b) Figure 15 Interference from a wedgeshaped film, producing localized fringes of equal thickness. Negative BvaluesB of r for both the TE and TM modes indicate a phase change of the E- or B-field vectors on reflection and will be discussed presently. Is the project practical? This holographic filter is subsequently used in the Fouriertransform plane, together with various test patterns having amplitude distributions g1 , g2 , Á , in the object plane. Practically speaking then, single films with zero reflectances cannot be fabricated. This behavior is illustrated in Figure 3. The gain in the Raman process is sufficient to produce a Raman laser in which the Raman gain compensates for the attenuation in a fiber loop, and a self-sustained oscillation at the overlap between a fiber ring mode frequency and the peak of the Raman gain bandwidth occurs. Use the fact that the Doppler frequency shift ¢n for light reflected from a moving object is twice that of light emanating from a moving object, or ¢n = 2nup>y, where n is the light frequency, y its velocity in the medium, and up is the component of the object velocity parallel to the light wave's propagation direction. Diffraction gratings are also sometimes used in wavelength-division multiplexing and demultiplexing systems in order to combine different-wavelength signals prior to launching them into an optical fiber and then to separate these signals once they have exited the fiber. 1 1 d 1 = + feff fo fe fofe (41) Eyepiece Objective O I ExP EnP f0 s0 f0 L fe s0 d Figure 28 Image formation in a compound microscope. Immediately upon passing through the pupil, light falls on the crystalline lens, a transparent structure about the size and shape of a small lima bean. To calculate the irradiance at the field point P in Figure 15a, a length of ¢y = 0.632 symmetrically placed about the origin of the Cornu spiral, as shown in Figure 15b, determines the endpoints of the chord FG used to calculate the irradiance at point P. In Figure 1a, plane wavefronts of coherent, monochromatic radiation (the wavefronts of the reference beam) illuminate a photographic plate. We wish to show that the Cauchy dispersion equation can be deduced from Eq. (39) under certain simplifying assumptions. The constraints placed upon the Gaussian beam by the cavity are, therefore, R1z12 = z111 + z20>z212 = RM1 (32) R1z22 = z211 + z20>z222 = RM2 (33) z2 - z1 = d (34) and Here, z1 and z2 are the coordinates of the two cavity mirrors. (Pump energy absorbed by the crystal, as we shall see in the next section, can be converted to Nd:YAG laser output.) a. Important in his considerations was the observation that light seemed to cast sharp shadows of objects, in contrast to water and sound waves, which bend around obstacles in their paths. 290 Chapter 11 Collimated beam Slit Fraunhofer Diffraction 11 Suppose that a CO2 gas laser emits a diffraction-limited beam at wavelength 10.6 mm, power 2 kW, and diameter 1 mm. Boston: Butterworth Publishers, 1980. We assume that the two sets of axes are similarly oriented, as in Figure 1. If scattered light is viewed from a point B on the y-axis, it will be found to contain E-vibrations along the z-direction, but not along the y-direction. This approach is useful for another reason. Solution ' ' The light has relative phase between E0x and E0y of wy - wx = e = tan-1 A 12 B = 0.148p. The amplitude of the cosine term in Eq. (30) is just the magnitude of the degree of coherence g , that is, ƒ g1t2 ƒ = 1 - t t0 (31) This quantity sets the limits of the variations in the interference term in Eq. (27) and thus controls the contrast or visibility of the fringes as a function of t. The dotted curve shows the photon number density Np in the cavity (multiplied by 20 so that both curves have similar vertical scales) as a function of time. If we had chosen to write E = Ue -i1kz - wt + f2 in Eq. (6), then we would have written q102 = z + iz0. The free spectral range, nfsr , of the transmittance. The electromagnetic field produced by this ideal monochromatic point source has perfect temporal and spatial coherence. [It may be somewhat simpler to implement the relation I W IS in Eq. (40) and then integrate, than to use Eq. (41) directly.] 10 Consider the limit described in problem 9. 10 Use the matrix approach to find the system matrix for the unaccommodated schematic eye of Table 2 and Figure 3. Diffraction Grating Spectrographs. As shown in Figure 7, surfaces of constant phase, that is, wavefronts, are then spherical surfaces centered at the source. Mirror surface R1 Mirror-lens combination R3 0.64 m R2 2 m w0( ) d 0.7 m Laser cavity t 4 mm 27 External beam waist Determine and w0( ) Characteristics of Laser Beams INTRODUCTION We now turn our attention to the nature of the optical beam generated by a laser. 11 Show that Eq. (19) is equivalent to the Doppler effect for light. The color temperature of a specimen of light is then the temperature of the blackbody with the closest spectral energy distribution. The window (Figure 6) operates in the same way as a single plate of the pile-of-plates analyzer. Consequently, without loss of generality, we shall consider an electromagnetic field of the form B E = E1x, y, z, t2xN (2) ' We shall find it convenient to represent this field by the complex field E such that ' E = Re1E2 ' This field component E satisfies the wave equation ' ' n2 0 2E §E - 2 2 = 0 c 0t 2 (3) Here, §2 = 02 02 02 + 0x2 0y2 0z2 is the Laplacian operator, n is the refractive index of the medium through which the field is propagating, and c is the wave speed in vacuum. How does the total wedge thickness compare with that of the flat plate in the position of maximum retardation? Fundamentally, the same effect is involved in the diffraction of light. During operation, tungsten gradually evaporates from the filament and deposits on the inner bulb surface, leaving a dark film that can decrease the light output by as much as 18% during the life of the lamp. 5 MODES OF SPHERICAL MIRROR CAVITIES A mode of an optical cavity is a self-replicating field distribution. 9 Taking values for refractive indices and separation of elements from the schematic of the unaccommodated eye given in Table 2 and Figure 3, determine the distance behind the cornea where an image is focused for (a) an object at infinity and (b) an object at 25 cm from the eye. (c) Construction used to relate distances y and w to matrix elements. As the object moves closer to the eye, the ciliary muscle tenses or contracts, squeezing or bulging the lens and resulting in decreased radii of curvature and a shorter focal length. See Figure 8b. But if the object OO¿ is moved to a position nearer to AS, at some point the lens rim becomes the limiting aperture. In a human retina there are about 7 million cones and 75 to 150 million rods. When the prism is made of some type of glass, its wavelength range is limited by the absorption of glass outside the visible region. Let a 2 * 2 matrix representing the polarizer operate on vertically polarized light, and let the elements of the matrix to be determined be represented by letters a, b, c, and d. Astigmatism can be corrected by removing tissue in an asymmetric manner, thus producing an eye whose refractive power is the same along any meridian. The expanded beam is then split by a semireflecting plate BS to produce two coherent beams. Figure 17 illustrates how three key rays—labeled 1, 2, and 3—each leaving a point P at the tip of an object, can be drawn to locate the conjugate image point P¿. At what instant is their superposition everywhere zero? 20 Show that Eq. (47) for a linear cavity reduces to Iout = T2IS g012L2 - ln11>S2 a b 2 1 - S for a cavity with R1 = 1. In addition, if the width of the etalon mode is less than the free spectral range of the cavity, only one cavity mode will be present in the laser output. If the index of diamond is 2.42, calculate the Brewster and critical angles for both (a) external and (b) internal reflections. The axial miss distance EI, due to rays from the extremities of the lens, provides the usual measure of longitudinal spherical aberration, whereas the distance IG in the paraxial image plane measures the corresponding transverse spherical aberration. Following the discovery of the ruby and helium-neon (He-Ne) lasers, many other laser devices, using different amplifying media and producing output at different wavelengths, were developed in rapid succession. Table 1 lists others, as well as several that depend on the third-order contribution to the polarization of the medium, P3 = e0x3E 3. That is, the overlap occurs if m¢l>2 = l1>2 Thus, the maximum wavelength separation that can be unambiguously resolved is ¢lmax = l1>m L l>m Here, l is the nominal wavelength of the incident light composed of the two closely spaced wavelength components l1 and l2 . A more dramatic increase in carrying capacity results from wavelength-division multiplexing, in which information is simultaneously carried in different wavelength channels through the same fiber. (7) and (8) and rearranging terms, / = sa1 + c h21R + s2 /¿ = s¿ a 1 + c Rs2 + h21R - s¿2 Rs¿ 2 h41R + s2 4R3s2 + db h41R - s¿2 4R3s¿ 2 1>2 (11) db 1>2 (12) Next, representing the quantities enclosed in square brackets by x in Eq. (11) and x¿ in Eq. (12), the square roots of the expression in outer parentheses may be approximated, again using the binomial expansion: 11 + x21>2 1 + x x2 2 8 (13) Thus, / sa1 + /¿ s¿ a 1 + x x¿ b 2 8 x¿ 2 x¿ b 2 8 (14) (15) 442 Chapter 20 Aberration Theory When all terms of order higher than h4 are discarded, there remains h21R + s2 / = sc1 + 2Rs2 /¿ = s¿ c 1 + + h21R - s¿2 2Rs¿ 2 h41R + s2 8R3s2 + - h41R - s¿2 8R3s¿ 2 h41R + s22 8R2s4 - d h41R - s¿22 8Rs¿ 4 (16) d (17) To find the aberration a(Q) for an axial object point, these expressions for / and /¿ can be introduced into Eq. (6). The effect of spherical aberration for a concave spherical mirror that images an axial object point is shown in Figure 6a. Here we have introduced a0 as the small-signal 11 : 02 loss coefficient. Since dl here is the minimum resolvable wavelength difference, the resolving power of the grating is, by Eq. (8), ℛ = mN (11) For a grating of N grooves, the resolving power is simply proportional to the order of the diffraction. The ray is a useful construct, although abstract in the sense that a light beam, in practice, cannot be narrowed down indefinitely to approach a straight line. Semiconductor materials can be engineered to have a variety of bandgap energies resulting in a variety of operating wavelengths. Birefringent Phase Matching A technique commonly used to circumvent the small coherence length of nonlinear crystals makes use of their birefringence. The distance between the plane containing the apertures and the plane of observation is 7 m, and the two slits are separated by 1.0 mm. PROBLEMS 2 1 A pulse of the form y = ae-bx is formed in a cos(0.36 − 2t/s) y = 11.6 sin(t + 0.402) E = 0.695 cos(0.349 − t/s) (a) 2 V/m (v) 0.2 V/m (t) = (2.48 cm) cos(2.51 − (20/s)t) (a) vg = vp [1 − (l/n)(dn/dl)] (b) vg < vp c/1.56 vp = c/1.5; vg = c/1.73 vg = A = constant 2(v/c)v0 14 cm; 1.57 cm; 0.785 cm; 0 cm/s; 1 seconds (a) 1.5 cm; 25 Hz; 20 cm; 5 m/s; opposite directions (b) 10 cm (c) −3 cm; 0 cm/s; 7.40 × 104 cm/s2 40 Chapter 4 1. Suppose that the birefringent material introduced in the light beam constitutes a half-wave plate with its fast axis (FA) vertical, as shown. Another means of classification distinguishes between those interferometers that make use of the interference of two beams, as in the case of the Michelson interferometer, and those that operate with multiple beams, as in the Fabry-Perot interferometer. The radiant flux 1£ e2 emitted per unit of solid angle 1v2 by a point source in a given direction (Figure 2) is called the radiant intensity, Ie . Figure 8 illustrates another application of ultrasonic holography that enables one to reveal objects under the surface of the ocean. Each film is lf>4 in optical thickness. The optic axes are as indicated. How many dark "lines" are seen across the entire spectrum? A crucial difference between particles like electrons and neutrons and particles like photons is that the latter have zero rest mass. 2. As we have seen, however, the phasor a1 , due to the first Fresnel zone, has an effective phase of p>2 behind that of the light reaching P along the axis. If the distance between the cavity mirrors is d, the cavity will support standing waves with wavelengths lm that satisfy the relation d = ma lm b 2 (25) where m is a nonzero integer. Furthermore, if the source point moves, the returning beam adjusts so that it continues to point to the source, the pointing and tracking property. Because of the rapid variation of the electric and magnetic fields, whose frequencies are 1014 to 1015 Hz in the visible spectrum, the magnitude of the Poynting vector in Eq. (39) is also a rapidly varying function of time. Thus, such a beam is a mode of the cavity. (New York: Holt, Rinehart and Winston, 1985). Two pencils of rays are drawn—one shaded, one clear—each limited by an aperture stop located (1) at some distance from the lens and (2) near the lens. Reading, MA: Addison-Wesley Publishing Company, 1957. Indices high enough to satisfy this condition are possible in infrared applications where large values of ns are available, as in the case of germanium with ns = 4. Such interferograms are approximated, for the purposes of Fourier-transform calculations, by periodic sampling. Principles of Optics, 5th ed. thick. Use the matrix approach. Flat-panel LCDs are much less bulky and can consume less power than CRT displays with comparably-sized viewing screens. The efficiency of deep-groove replicas may be better than that of the master because the replication process transfers the smooth parts of the groove faces from bottom to top, improving performance. to the irradiance in the field incident on the Fabry-Perot. The two beams intersecting at P superpose and interfere. The second approximation identifies the angle u with the angle between the optical axis OX and the line drawn from the midpoint O between holes to the point P at the screen. Determine the change in refractive index and the phase difference produced by an applied voltage of 426 V when the light beam is from a He-Ne laser at 632.8 nm. The nearest practical film material with a matching index is MgF2 , with n = 1.38. Since y = c>n1, this result is conveniently expressed as a temporal pulse spread per unit length, in the form modal distortion 1step-index fiber2: d a n1 n1 - n2 t b = b a c n2 L (14) Example 2 Suppose the fiber has a core index of 1.46 and a cladding index of 1.45. n0 n2 n0 n2 n1 n(r) n 2a r n2 n0 n2 n0 (a) n0 n2 n0 n2 n1 n1 n n2 n0 n2 n1 n0 n2 n(r) n2 n0 (c) Figure 10 (a) Profile of a graded-index (GRIN) fiber, showing a parabolic variation of the refractive index within the core. Binoculars (Figure 33) afford more comfortable telescopic viewing, allowing both eyes to remain active. The message output may then be communicated by loudspeaker (audio), by cathode-ray tube (video), or by computer input (digital). We have already seen that anisotropy in the binding forces affecting the electrons of a material can lead to anisotropy in the amplitudes of their oscillations in response to a stimulating electromagnetic wave and hence to anisotropy of absorption. Furthermore, in the B theory described here, the E-field wave function is a scalar function whose absolute square yields the irradiance. The converging incident rays 1, 2 and 3 determine an image location between the lenses, which acts as a virtual object VO for the optical system. Optical Interferometry with an arm length L of even 10 km. New York: John Wiley and Sons, 1991. Interference occurs between the light reflected from each of two mirrors, M1 and M2 , 1 A theoretical explanation for phase changes on reflection results from an analysis based on Maxwell's equations and requires identification of the state of polarization of the light. If the diffraction pattern is focused by a 50-cm lens, what is the linear separation of a 1-Å interval in the vicinity of 500 nm? 28 a. 499 Fresnel Equations 1 0.8 0.6 0.4 TE 0.2 r TM 0 0.2 up 33.7 uc 41.8 0.4 0.6 Internal reflection (glass-to-air) 0.8 1 0 10 20 30 40 50 60 Angle of incidence u 70 80 Figure 5 Reflection coefficient for the case of internal reflection with n = n1>n2 = 1>1.50. These are the horizontal arrows shown in Figure 16c. (In a conductor, the conduction and valence bands overlap.) In an intrinsic semiconductor, the atoms bond so as to "fill" the outer shells of the atoms. 6 NEWTON'S RINGS Since Fizeau fringes are fringes of equal thickness, their contours directly reveal any nonuniformities in the thickness of the film. Find a difference in path length between the two arms of the fiber interferometer ¢L that will efficiently demultiplex a signal containing wavelength components l1 = 1550.8 nm and l2 = 1550.0 nm. The optical path length ¢ associated with two traversals of the thin film is ¢ = 2n1t cos1ut12. As shown in Figure 18, the pattern differs in two important respects from the Viewing microscope Beam splitter Light source Collimating lens R R tm tm Lens rm Optical flat (a) (b) Figure 17 (a) Newton's rings apparatus. These and others may be found in standard references.9 9 For example, see Amnon Yariv, Optical Electronics, 3d ed. This neglect is justified in problem 7. In this process, two strong, counterpropagating pump beams of complex amplitude A 1 and A 2 interact with a third, weaker signal or probe beam of complex amplitude A 3 in a nonlinear medium with inversion symmetry. The pinhole camera is not useful in freezing the action of moving objects. Note that this description of the production of a Q-switched pulse has much in common with the description of the first pulse shown in Figure 13. Thus two lenses of the same material, separated by a distance equal to the average of their focal lengths, exhibit zero longitudinal chromatic aberration for the wavelength at which the focal lengths are calculated. The B E-vector makes an angle of 30° relative to the y-axis. In fact, often n0 = ns because the media bounding the film are identical, as in the case of a water film (soap bubble) in air. The resultant phasor of N zones is also in the direction of a1 . t H1 (t0 t) 2t0 4t0 t 3t0 t0 p (b) Simplification gives the important result g1t2 = eivt8ei[w1t2 - w1t + t2]9 The time average expressed in this equation may be calculated as 8ei[w1t2 - w1t + t2]9 = T 1 ei[w1t2 - w1t + t2] dt T L0 (28) where T is a sufficiently long time. The lens has a refractive index of 1.60 and radii r1 = 36 cm and r2 = - 18 cm. Entrance Window (E nW) The entrance window is the image of the field stop formed by all optical elements preceding it. The rate equations describing the interaction of the two-state atomic system with a broadband electromagnetic field then have the form dN2 = - A 21N2 - B21r1n02N2 + B12r1n02N1 dt (4) dN1 = + A 21N2 + B21r1n02N2 - B12r1n02N1 dt (5) and Note that dN2 dN1 = dt dt since we are accounting only for processes that couple the energy levels 2 and 1. In this case, Eq. (8) should be modified to give ' A E0 = c d iB counterclockwise and rotation ' A E0 = c d - iB clockwise rotation (b) Figure 6 Elliptically polarized light for the case ¢w = p>2. 15 Unpolarized light passes through a linear polarizer with TA at 60° from the vertical, then through a QWP with SA horizontal, and finally through another linear polarizer with TA vertical. As can be seen from the figure and by examination of Eq. (24), the requirement that nodes exist at the mirror positions restricts the wavelengths 122 Chapter 5 Superposition of Waves Mirror Mirror l\2 Figure 6 Standing wave mode of a laser cavity with mirror spacing d. It is routinely used by physicians to examine regions of the heart, stomach, lungs, and duodenum. Figure 10 Geometry for a He-Ne laser system. The other is selected with a reflectivity somewhat less than 100% to allow part of the internally reflecting beam to escape and become the useful laser output beam. An identical chamber is placed in path 2 to maintain equality of optical paths. The phase conjugate output of the signal beam is the beam shown as A 4 . Thus the optical isolator effectively isolates the optical system from stray retropulses. The transmittance of the beam can be expressed by the relation10 I = Imax sin2 a p V b 2 VHW (9) and is plotted in Figure 5. However, in fact, one must check to see if the mode number m associated with this answer is an integer. Hold a pencil a foot or so in front of you at eye level. Determine the initial phase and sketch the wave when l = 10 cm and x0 = 0, 56 , 52 , 5, and - 12 cm. Interference maxima occur for a = pp, with p = 0, ; 1, ; 2, Á , or when interference maxima: pl = a sin u (29) When the conditions expressed by Eqs. Their overall attenuation is at least an order of magnitude higher than for glass. Notice that Tmax = 1 regardless of r and that Tmin is never zero but approaches this value as r approaches 1. In contrast, in a mode-locked system the loss modulation occurs once each round-trip in the following fashion. Because of dispersion, an additional chromatic aberration appears, even for paraxial optics, in which images formed by different colors of light are not coincident. In contrast to the stimulated Raman process, stimulated Brillouin scattering can lead to significant attenuation and distortion of signal power in a given fiber channel when the signal power is just a few mW. If the object is 50 cm from the lens, determine (a) the transverse spherical aberration and (b) the diameter of the blur circle in the paraxial focal plane. Still other losses become important over longer lines wherever connectors, couplers, or splices are necessary. The transmitted wave at a refraction can be represented as B # B Et = E0tei1kt r - vt2 where, according to the coordinates chosen in Figure 1, kt # Br = kt 1- sin ut xN - cos ut zN 2 # 1x xN + z zN 2 B kt # Br = kt 1- x sin ut - z cos ut2 B We can express cos ut as cos ut K 21 - sin2 ut = B 1 - sin2 u n2 where we have used Snell's law, n sin ut = sin u in writing the last equality. Note that at all points on a given plane wavefront c have the same value. An empirical relation giving the variation of K with frequency is K = 1 + [A>1v20 - v22] where A and v0 are constants for the gas. For example, in gallium arsenide (GaAs), gallium has three outer-shell electrons and arsenic has five outer-shell electrons. 335 Matrix Treatment of Polarization relative amplitudes and phases of these only on the complex amplitude, written vector, ' ' E0x E0 = c ' d = E0y components, we need concentrate as a two-element matrix, or Jones y A x E eiwx c 0x iwy d E0ye (5) (a) Let us determine the particular forms for Jones vectors that describe linear, circular, and elliptical polarization. Also, sp is the stimulated emission cross section for the 3-to-0 transition and we have again ignored, for simplicity, level degeneracies. This method allows mass production of many embossed holograms simply and inexpensively. These "extra" electrons act as negative charge carriers. London: Chapman and Hall Ltd., 1969. 25 Produce curves like those shown in Figure 13 for the parameters given in the figure caption except let (a) k = 10-8 s-1, (b) k = 10-6 s-1, (c) g0>gth = 1.1, and (d) g0>gth = 4. Using light of wavelength 589 nm, the fringe pattern is found to shift by 35 fringes. Lett. As a result, when a harmonic wave in the form of Eq. (52) is substitutB ed into Eq. (53), we find that the propagation vector k must have the complex magnitude 1>2 ' v s bd k = c1 + ia e0v c (54) Since the refractive index n is related to k by n = 1c>v2k, the refractive index is now the complex number 1>2 s ' n = c1 + ia bd e0v (55) ' n = nR + inI (56) or we write, in general, ' ' where Re 1n2 = nR and Im 1n2 = nI . Distances are in meters and time in seconds. This represents one to two orders of improvement Figure 13 Scan of the (scaled) FabryPerot transmittance of two wavelength components of comparable strength. As early as 1927, Michelson suggested the possibility of photographing straight interference fringes using an optical system such as that shown in Figure 7a. The surfaces are hyperbolic, since Eq. (24) is precisely the condition for a family of hyperbolic curves with parameter m. Under sodium light (589 nm) normally incident on the air film formed between the slides, one observes exactly 40 bright fringes from the edges in contact to the edge of the tin foil. 9 A reflection grating is required that can resolve wavelengths as close as 0.02 Å in second order for the spectral region around 350 nm. 17. Once formed, this pulse passes through the gate, bounces off the mirror, and passes through the gate again before the gate closes. The third term is given by EH3 = r2ei12w2sei1vt - u2 (12) 378 Chapter 16 Holography Incident light ER First-order virtual image a a 2a EH2 H a EH3 First-order real image EH1 Zerothorder Figure 3 Reconstruction of hologram formed in Figure 2a. Aberration Theory 21 Design an achromatic doublet of 517/645 crown and 620/380 flint glasses that has an overall focal length of 20 cm. Also find the displacement at x = 10 cm and t = 0. Thus, the exit pupil is the image of the controlling aperture stop formed by the imaging elements following it (or to the right of it in our figures). Signal transmitters Signal receivers 1 2 3 4 Multiplexer 1 1, 2, 3, 4 Fiber 2 3 4 Demultiplexer Systems that utilize such a large number of wavelength channels are sometimes said to employ dense wavelength-division multiplexing (DWDM). The irradiance at point P– is thus given by IP– = I01BE22 6 IP As indicated in the preceding relation, since BE 6 OE, the irradiance at P– is less than that at P. For an ideal laser field, this inherent uncertainty is given by ¢n = 2n 3 The responsivity of an InGaAs p-i-n photodiode is 0.8 A/W at a wavelength of 1.5 mm. (New York: Holt, Rinehart and Winston, 1985), Ch. 16. This time-varying index of refraction in turn gives rise to a time-dependent phase shift of the signal. The Coddington shape factor below each shape serves to classify them. Sections of quartz or calcite and thin sheets of mica can be used to demonstrate the production of colors by polarization. The same scene is viewed, though with slightly varying perspective, as the opening is moved to different parts of the window. As the object in the aperture plane is translated along its x-axis, the light energy in the direct beam varies, producing the correlation function £ 121qx2. What is the thickness of the sheet? The spherical mirror described by Eq. (12) yields, for a plane mirror with R : q , s¿ = - s, as determined previously. The coordinate z is, of course, real so q(0) must be complex. 57 Optical Instrumentation Entrance window EnW: Exit window ExW: The image of the field stop formed by the optical elements (if any) that precede it. It can be shown10 that neff = n1 sin w. A more typical stripe-heterojunction device is shown in Figure 19. The power of this lens is P = = = f 0.51 m 1.96 diopters. For concreteness, let us assume that the pump is a laser of frequency np = (E3 - E0)/h and irradiance Ip . For nearby points, imaging is not perfect. (34) to (41) for ray tracing through an arbitrary number of refracting, spherical surfaces. 550 nm C C C O O O O Side view of zone plate r2 r3 P r1 r0 Observation point Collimated light C clear O opaque Figure 21 25 cm Problem 10. As demonstrated in Example 2, beam-shaping optics can control the size of the beam waist and thus control the length of the collimated region. To experience proper binocular vision without double vision, the images of an object must fall at corresponding points on each retina. Include a sketch, roughly to scale, and do a ray diagram for a finite object of your choice. The acousto-optic interaction then consists of the interaction or collision of these particles in which both enB B k k , ergy and momentum are conserved. The applied voltage creates a field that is perpendicular to the beam direction. Real and imaginary parts of the complex refractive index are 1.5 and 5.3, respectively, for light of 589.3 nm. A relative phase shift of p occurs between the externally and internally reflected beams, so that, equivalently, an additional path difference of l>2 is introduced between the two beams. One filter has a "broad" transmission width of 100 nm, whereas the other has a "narrow" pass band of 10 nm. 9 Referring to Example 2 and Figure 10, (a) determine an expression for q1 at the plane mirror; (b) solve Eq. 19 for the spot-size value w1 ; (c) obtain a numerical value for q1 ; (d) multiply q1 by the ABCD matrix to obtain q2 ; (e) use Eq. (17) and q2 from part (d) to obtain / and w1/2. If object and image are interchanged, the same system produces pincushion distortion. c d 2i 2 g. Calculate the chromatic resolving power of crown and flint prisms in the vicinity of the Fraunhofer D line, if each prism base is 75 mm in length. Determine the locations of the first three maxima and minima as the photocell approaches the screen. In comparing formulas for divergence angles, care must be taken to distinguish between the full angular spread illustrated in Figure 4 and the half-angle spread. If the aperture is a circle of radius 1 cm, centered on axis, how many half-period zones does it contain? One of the mirrors is also movable along the direction of the beam by means of an accurate track and micrometer screw. Therefore, equal times imply equal values of the product nx, called the optical path length. The nonlinearity of silica molecules in optical fibers leads to the generation of, primarily, a Stokes field shifted from the fundamental frequency by an amount in the range 1012 – 1013 Hz. The attenuation, due to stimulated Raman scattering, of the power carried by an optical fiber is typically not significant unless the power carried by the fiber approaches 1 W. It is helpful to note the similarity between the behavior of ordinary spherical waves encountered in geometrical optics and Gaussian spherical waves encountered here. The binomial expansion then permits expansion to the fourth power in h: cos f 1 - h2 h4 2 2R 8R4 (10) Introducing Eq. (10) into Eqs. The group velocity for this pulse would be yg = yp c1 + = yp c1 - l dn l 4825 nm2 a bd` = yp c1 + a b1-22 d ` n dl n l3 l = 500 nm l = 500 nm 9650 nm2 d` nl2 l = 500 nm yg = 11.942 * 108 m>s2c1 - 9650 nm2 d = 1.893 * 108 m>s 11.54482 1500 nm22 The group and phase velocities do not differ greatly for visible pulses propagating through glass because the index of refraction of glass varies only slightly across the visible spectrum. In general, however, there is a complex exchange of energy between the field and atomic population in such a system that makes the pulse characteristics difficult to control. The average power in the Q-switched system is the power averaged over the time T. For h V p and h V q, a binomial expansion approximation gives r¿ = 1p2 + h221>2 = pa 1 + h2 1>2 h2 b pa 1 + b p2 2p2 z W y r S p O r q P x (a) z r h r S P q p Figure 11 (a) Cylindrical wavefronts from source slit S are diffracted by a rectangular aperture. The trough-like depression evident in the interference pattern was made by evaporating the film over a thin, straight wire. Optical Radiation Measurements Series, Vol. However, in 1916 Einstein was able to develop relationships between these so-called A and B coefficients, without relying on a fully quantum treatment, by considering the situation in which the atoms in the system come to thermal equilibrium with an electromagnetic field. Thus, if bare optic fibers are packed closely together in a bundle, there is some leakage between fibers, a phenomenon called cross talk in communications applications. What is light? These are ray aberrations. Which relation, the one from part (b) or the one given in Eq. (43), is correct when S is not close to 1? Using Equation (17) in the trial solution given in Eq. (10) leads to U1r, z2 = E0eip1z2eikr >2R1z2e -r >w 1z2 2 2 2 (18) We see that the spot size w(z) parameterizes the exponential drop-off of the electric field strength in the transverse 1r2 direction. For example, the reflectance becomes R = 121R7 + R 2 (38) 2 REFLECTANCE AT NORMAL INCIDENCE We apply the theory now for normally incident light, the case most commonly found in practice. Solution Using Eq. (25) we see that the parameter L = pq>1p + q2 = 12021302> 120 + 302 = 12 cm. The pattern is similar to that of Figure 2 for a slit, except that the pattern for a circular aperture has rotational symmetry about the optical axis. The corresponding point z on the wavefront is z = a p 20 by = 112 = 0.4 mm p + q 50 The intersection of the dashed line (Figure 15a) with the wavefront at the slit thus occurs 0.4 mm above the center of the slit or 0.1 mm below the upper slit edge. Since each sample is described using 8 bits, the required data rate is 96 Mbps (megabits per second). (c) Gain saturation has reduced the gain coefficient so that only the mode nearest linecenter survives. The variation of neff is quite small because n1 - n2 is, in practice, quite small. A comprehensive treatment of fiber optics requires a wave approach in which Maxwell's equations are solved in a dielectric medium, subject to the boundary conditions at the fiber walls. Example 3 a. For a laser system like that shown in Figure 16a, a cavity mode of a given frequency will be present in the laser output only if it is amplified by the laser gain medium and satisfies also the low loss condition imposed by both the laser cavity and the etalon. The motion of the fringe pattern thus reverses as one of the mirrors is moved continually through the point of zero path difference. Although there are also bound electrons, the response of the free electrons dominates the electrical and optical properties of the medium. The reflectance calculated in part (a) is also valid for an internal reflection as light leaves the glass going into air. Another means of exciting nonlinear behavior without using high beam irradiances is to choose the exciting optical frequency near a resonant frequency of the oscillating dipoles, a technique widely utilized in nonlinear spectroscopy and known as resonance enhancement.2 B The polarization of a linear medium by an electric field E is usually written in the form B B P = e0xE (1) where x is the susceptibility and e0 is the vacuum permittivity. Reading, MA: Addison-Wesley Publishing Company, 1974. (c) Several ray paths within a GRIN fiber, showing their self-confinement due to continuous refraction. The inverse process of decomposition of a given waveform into its harmonic components is called Fourier analysis. All the preceding discussion of the fringes from a Michelson interferometer has been in terms of virtual fringes of equal inclination. 1973), 1563. Determine (a) the angular magnification of a distant object, (b) the focal length of the ocular, (c) the diameter of the exit pupil, (d) the eye relief, and (e) the field of view in terms of feet at 1000 yd. Thrierr, Atlas of Optical Phenomenon, Plate 10, Berlin: Springer-Verlag, 1962.) (b) Fabry-Perot interferometer, used with a point source and a variable plate spacing. Hence it is also called a folding or superposition integral. If the telescope is focused on a telephone pole 30 m away, how much of the post falls between millimeter marks on the graticule? Since R1 : q at the plane mirror, 1 1 il il = + = 2 q1 R1 pw1 pw21 5 595 or q1 = - ipw21 l Amnon Yariv, Quantum Electronics 3d ed. What is the maximum aperture diameter? Widths and heights of the blur pattern can be found at any position of the screen using the geometry apparent in Figure 32a and b, respectively. "Basic Optical Instruments." In Geometrical and Instrumental Optics, edited by Daniel Malacara. Any polarization of refracted rays? By continuing this process, one sees that the phasors approach a smooth curve, which spirals into a limit point E, the eye of the spiral. For P–, the point O– marks the center of the wavefront, just as the point O marks the center of the wavefront relative to point P. In Figure 15 the mirror shown is convex, and two 3 The refinement of lens construction using injection molding technology has eased the production of lenses with aspherical surfaces. Show that if Brewster's angle is satisfied for a TM light beam entering a parallel plate (a Brewster window), it will also be satisfied for the beam as it leaves the plate on the opposite side. For example, a very large letter may be such that it subtends angles of 5¿ and 1¿ of arc for a test distance of, say, 300 ft. UV radiation from the sun is linked to a variety of health risks. Suppose we view the circular systems 197 Optical Interferometry near their center, so that cos u 1. Phase Retarder The phase retarder does not remove either of the orthogonal components of B the E-vibrations, but rather introduces a phase difference between them. Object and image planes are also shown. The transmitting portion of the aperture plane is an annular ring of inner radius 0.500 mm and outer radius 0.935 mm. Elements A and L1 have no "optics" to their left, so each subtends a half-angle directly: For element A: uA M 1.5>15 = 0.1 rad For element L1: uL1 M 3>18 = 0.17 rad Optical System A L1 L2 P f 1 6 cm f 2 10 cm 3 cm 1.5 cm O F1, F2 F1 3 cm 4 cm 18 cm Figure 4 Sketch of optical system of Example 1. New York: Springer-Verlag, 1981. In the normal eye—and before the normal aging process robs the lens of its elasticity and ability to reshape itself—accommodation produces faithful retinal images of objects from distant points (infinity) to nearby 426 Chapter 19 Optics of the Eye points about one foot away. 219 220 Chapter 8 Optical Interferometry Since the beams heading towards the detector encounter the 50-50 beam splitter as they enter and exit the respective interferometer arms, P1 = P2 = P0>4 and Pdet = P0 P0 P0 P0 + + 2 cos d = 11 + cos d2 4 4 4 2 Note that the detected power varies between zero and the full laser power P0 as cos d varies from - 1 to 1. 13 A plane reflection grating with 300 grooves/mm is blazed at 10°. In such a case, the behavior of the lens as a whole, due to the addition of the powers of the two surfaces, may not reduce to that of the simple plano-convex or plano-concave lens described here. (19) and (20). (Hint: First find the effect of the HWP alone on the incident light.) 6 Write the equations for the electric fields of the following waves in exponential form: a. As the spacing d is varied, the detector records the interference pattern as a function of time in an interferogram. Develop your answer based on the ratio A21>B21 and the meaning of the A21 and B21 coefficients. Or, as in Figure 17b—still for a concave mirror—ray 3 appears to come from the point C to its left, strikes the mirror, and reflects back along itself. 14.6 m; 58.3 m; 131.2 m; 364.5 m 20. Since typical radii of curvature for the grating may be around 6 m, the 305 The Diffraction Grating Mirror Slit Plate Figure 12 grating. Solution The first lens is convex: f1 = + 15 cm, s1 = 25 cm. Complete incoherence: t : t0 and ƒ g ƒ = 0 Ip = I1 + I2 Ip = 2I0 , V = for equal beams 2I0 - 2I0 = 0 4I0 2. That is, switching to the low-Q state prevents additional relaxation oscillations characteristic of the approach to steady state. When illuminated, incoherent imaging of the test pattern takes place. The angles of incidence and refraction, u and u¿, are related by Snell's law. Optimum thicknesses for silver coatings are around 50 nm. As in the corresponding figure for a medium that is homogeneously broadened (Figure 10), let us consider a case in which the small-signal gain coefficient at line center g01n02 is twice the threshold gain coefficient gth . 4 If the following represents a traveling wave, determine its velocity (magnitude and direction), where distances are in meters. Gradually it became clear, to a large extent through the reflections of Niels Bohr and especially in his principle of complementarity, that photons and electrons were neither waves nor particles, but something more complex than either. 7 A number of dichroic polarizers are available, each of which can be assumed perfect, that is, each passes 50% of the incident unpolarized light. A representative reflected ray is DL, shown perpendicular to the reflected wavefront. The parameter q(z) is often called the complex radius of curvature of the beam. Find the threshold gain coefficient for this cavity. (b) Phasor diagram for circular Fresnel zones. The dotted curves indicate the transmittance of the two wavelength components considered separately, and the solid curve is the scaled transmittance when both components are present in the input field. Substituting Eq. (36) into Eq. (37) and performing the differentiation of a product, yg = d dv = 1kyp2 dk dk yg = yp + ka dyp dk b (38) When the velocity of a wave does not depend on wavelength, that is, in a nondispersive medium, dyp>dk = 0, and phase and group velocities are 127 Superposition of Waves equal. Optics, 9th ed. Since the focal length of a lens is dependent on the index of refraction of the lens material, focal lengths and image positions differ for different wavelength components of the light used in the optical system. The beam remains normal at all interfaces, so that all angles of incidence, reflection, and refraction are zero. Point source P1 P2 Figure 17 Portion of the wavefronts associated with a perfectly coherent light field produced by an ideal monochromatic point source. The aberration known as spherical aberration results from the first term, 4 0C40r , in Eq. (25). In addition, an example of a more complicated Fresnel pattern than those considered here is given in Figure 18. Collimation of a Gaussian Beam A collimated laser beam is a Gaussian beam with a long waist, as shown in Figure 11. The physics of the process is, of course, the same as that for X-ray diffraction from crystalline planes, governed by the Bragg equation, ml = 2d sin u d sin u Figure 6 Constructive interference of reflected waves from planes of separation d is governed by the Bragg equation, ml = 2d sin u. 198 Chapter 8 Optical Interferometry Figure 3 Deformation of fringes of equal thickness in the neighborhood of a candle flame. (17) v¿ v and accordingly B B k¿ k The vector triangle (Figure 12) for the wave vectors then shows that, B B ƒ k ƒ S = 2 ƒ k ƒ sin u, or, in terms of wavelength, l = 2lS sin u (18) which is Bragg's equation, with m = 1. The two choices of angle grew out of the best data available to Snellen on the minimum separable resolution of the eye. In the formation of holograms as shown in Figure 1a, the sinusoidal irradiance at the plate can fall to zero at points of destructive interference when the signal and reference beams are equal in amplitude. From Eq. (11), d = 2u - 2u¿ (12) A = 2u¿ (13) and from Eq. (6), Together these allow us to write d + A 2 u¿ = A 2 sin a A + d b = n sin a b 2 2 and u = (14) so that Eq. (1)

becomes or n = sin[1A + d2>2] sin1A>22 (15) 63 Optical Instrumentation Eq. (15) provides a method of determining the refractive index of a material that can be produced in the form of a prism. Thus the oscillating dipoles radiate more energy in the shorter-wavelength (higher-frequency) region of the visible spectrum than in the longer-wavelength region. If one dispenses with the slit in Figure 4 and merely assumes an original beam of constant irradiance across a finite width b, all our results follow in the same way. Thus, geometrical optics forms a special case of physical optics in a way that may be summarized as follows: limit 5physical optics6 = 5geometrical optics6 l:0 Since the wavelength of light—around 500 nm—is very small compared to ordinary objects, early unrefined observations of the behavior of a light beam passing through apertures or around obstacles in its path could be handled by geometrical optics. In this chapter, we examine the property of coherence in greater detail, distinguishing between longitudinal coherence, which is related to the spectral purity of the source, and lateral or spatial coherence, which is related to the size of the source. Humans "see" different wavelengths of light as different colors. Recall that cylindrical waves can be expressed mathematically in the same form as spherical waves, except that the amplitude decreases as 1> 1r so that the irradiance decreases as 1/r. The oppositely directed waves can then be written as E1 = E0 sin1vt + kx2 Á to the left E2 = E0 sin1vt - kx - wR2 Á (19) to the right (20) Here, wR is included to account for possible phase shifts upon reflection. If the irradiance IP at some point P on the screen is zero, what is the phase difference between light arriving at P from neighboring slits? The effect of the array of point sources along the slits, each set producing its own fringe system as just described, is simply to elongate the pattern parallel to the fringes, without changing their geometrical relationships. Bellingham, WA: SPIE Optical Engineering Press, 1989. Consider, however, the arbitrary path ACB. The helium-neon laser gain medium is capable of supporting laser light of wavelengths in the range from l1 = 632.800 nm to l2 = 632.802 nm. Exit Pupil (E xP) We have described the EnP of an optical system as the image of the AS one sees by looking into the optical system from the object. 424 Chapter 19 Optics of the Eye When the radiation consists of a spread of wavelengths, the radiometric and photometric terms may be functions of wavelength.