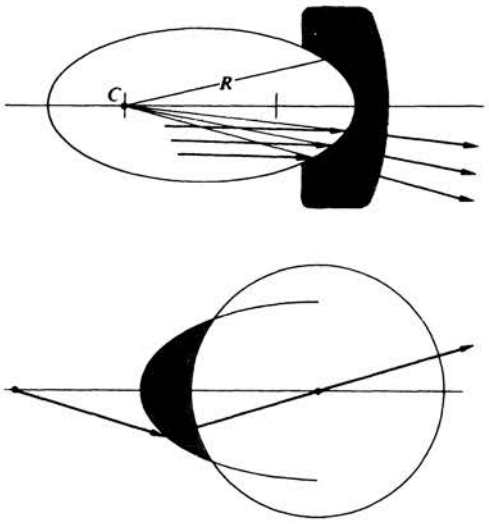
5.4 From Fig. 5.4 a plane wave impinging on a concave elliptical surface becomes spherical. If the second spherical surface has that same curvature, the wave will have all rays normal to it and emerge unaltered.



5.8 First surface: $\dfrac{n_1}{s_o} + \dfrac{n_2}{s_i} = \dfrac{n_2 - n_1}{R}$

$$\frac{1}{1.2} + \frac{1.5}{s_i} = \frac{0.5}{0.1}$$

$s_i = 0.36$ m (real image 0.36 m to the right of first vertex). Second surface $s_o = 0.20 - 0.36 = -0.16$ m (virtual object distance).

$$\frac{1.5}{-0.16} + \frac{1}{s_i} = \frac{-0.5}{-0.1}, \qquad s_i = 0.069$$

Final image is real ($s_i > 0$), inverted ($M_T < 0$), and 6.9 cm to the right of the second vertex.

5.13 From Eq. (5.8), $1/8 + 1.5/s_i = 0.5/-20$. At first surface, $s_i = -10$ cm. Virtual image 10 cm to left of first vertex. At second surface, object is *real* 15 cm from second vertex.

$$1.5/15 + 1/s_i = -0.5/10, \qquad s_i = -20/3 = -6.66 \text{ cm}$$

Virtual, to left of second vertex.

5.15 $s_o + s_i = s_o s_i/f$ to minimize $s_o + s_i$,

$$\frac{d}{ds_o}(s_o + s_i) = 0 = 1 + \frac{ds_i}{ds_o}$$

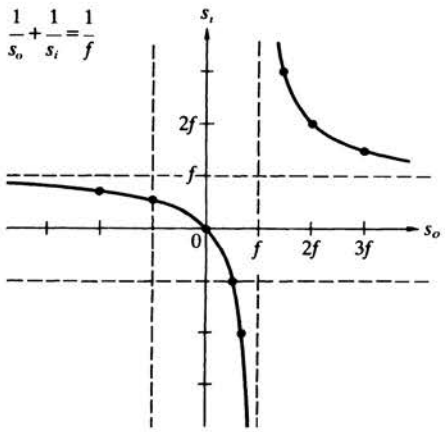
$$\text{or} \quad \frac{d}{ds_o}\left(\frac{s_o s_i}{f}\right) = \frac{s_i}{f} + \frac{s_o}{f}\frac{ds_i}{ds_o} = 0$$

$$\text{Thus } \frac{ds_i}{ds_o} = -1 \quad \text{and} \quad \frac{ds_i}{ds_o} = -\frac{s_i}{s_o}, \quad \therefore \quad s_i = s_o$$

The separation would be maximum if either were ∞, but both could not be. Hence, $s_i = s_o$ is the condition for a minima. From Gaussian equation, $s_o = s_i = 2f$.

5.16 $1/5 + 1/s_i = 1/10$, $s_i = -10$ cm virtual, $M_T = -s_i/s_o = 10/5 = 2$ erect. Image is 4 cm high. Or $-5(x_i) = 100$, $x_i = -20$, $M_T = -x_i/f = 20/10 = 2$.

5.17 $1/s_o + 1/s_i = 1/f$



5.19 $s_i < 0$ because image is virtual. $1/100 + 1/-50 = 1/f$, $f = -100$ cm. Image is 50 cm to the right as well. $M_T = -s_i/s_o = 50/100 = 0.5$. Ant's image is half-sized and erect ($M_T > 0$).

5.21 $1/f = (n_l - 1)[(1/R_1) - (1/R_2)]$

$$= 0.5[(1/\infty) - (1/10)] = -0.5/10$$

$$f = -20 \text{ cm}, \qquad \mathcal{D} = 1/f = -1/0.2 = -5 \text{ D}$$

5.24

(a) From the Gaussian lens equation

$$\frac{1}{15.0 \text{ m}} + \frac{1}{s_i} = \frac{1}{3.00 \text{ m}}$$

and $s_i = +3.75$ m.

(b) Computing the magnification, we obtain

$$M_T = -\frac{s_i}{s_o} = -\frac{3.75 \text{ m}}{15.0 \text{ m}} = -0.25$$

Because the image distance is positive, the image is *real*. Because the magnification is negative, the image is *inverted*, and because the absolute value of the magnification is less than one, the image is *minified*.

(c) From the definition of magnification, it follows that

$$y_i = M_T y_o = (-0.25)(2.25 \text{ m}) = -0.563 \text{ m}$$

where the minus sign reflects the fact that the image is inverted.

(d) Again from the Gaussian equation

$$\frac{1}{17.5 \text{ m}} + \frac{1}{s_i} = \frac{1}{3.00 \text{ m}}$$

and $s_i = +3.62$ m. The entire equine image is only 0.13 m long.

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5.28 The first thing to find is the focal length in water, using the Lensmaker's Formula. Taking the ratio $f_w/f_a = f_w/(10\text{ cm}) = (n_g - 1)/[(n_g/n_w) - 1] = 0.56/0.17 = 3.24$; $f_w = 32$ cm. The Gaussian lens formula gives the image distance: $1/s_i + 1/100\text{ cm} = 1/32.4$ cm; $s_i = 48$ cm.

5.29 The image will be inverted if it's to be real, so the set must be upside down or else something more will be needed to flip the image; $M_T = -3 = -s_i/s_o$; $1/s_o + 1/3s_o = 1/0.60$ m; $s_o = 0.80$ m. hence $0.80\text{ m} + 3(0.80\text{ m}) = 3.2$ m.

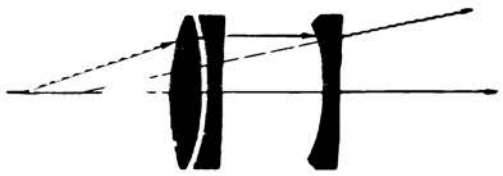
5.30
$$\frac{1}{f} = (n_{lm} - 1)\left(\frac{1}{R_1} - \frac{1}{R_2}\right)$$
$$\frac{1}{f_w} = \frac{(n_{lm} - 1)}{(n_l - 1)}\frac{1}{f_a} = \frac{1.5/1.33 - 1}{1.5 - 1}\frac{1}{f_a} = \frac{0.125}{0.5}\frac{1}{f_a}$$
$$f_w = 4f_a$$

5.34 $1/f = 1/f_1 + 1/f_2$. $1/50 = 1/f_1 - 1/50$. $f_1 = 25$ cm. If R_{11} and R_{12}, and R_{21} and R_{22} are the radii of the first and second lenses,
$$1/f_1 = (n_l - 1)(1/R_{11} - 1/R_{12}), \qquad 1/25 = 0.5(2/R_{11})$$
$$R_{11} = -R_{12} = -R_{21} = 25\text{ cm}$$
$$1/f_2 = (n_l - 1)(1/R_{21} - 1/R_{22})$$
$$-1/50 = 0.55[1/(-25) - 1/R_{22}]$$
$$R_{22} = -275\text{ cm}$$

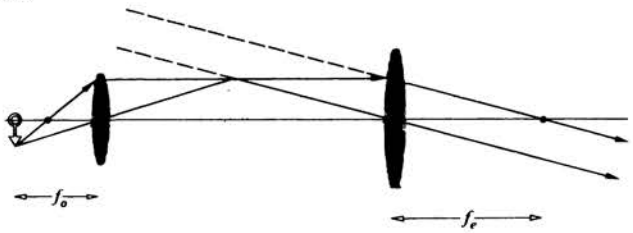
5.35
$$M_{T_1} = -s_{i1}/s_{o1} = -f_1/(s_{o1} - f_1)$$
$$M_{T_2} = -s_{i2}/s_{o2} = -s_{i2}/(d - s_{i1})$$
$$M_T = f_1 s_{i2}/(s_{o1} - f_1)(d - s_{i1})$$

From Eq. (5.30), on substituting for s_{i1}, we have
$$M_T = \frac{f_1 s_{i2}}{(s_{o1} - f_1)d - s_{o1}f_1}$$

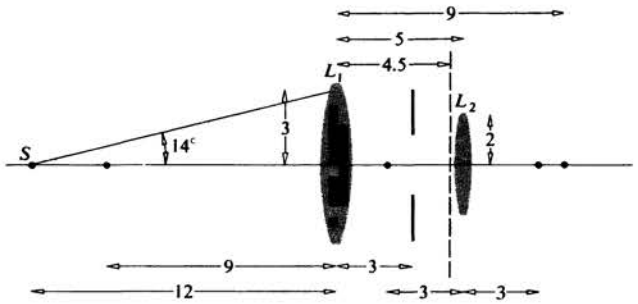
5.37 First lens $1/s_{i1} = 1/30 - 1/30 = 0$, $s_{i1} = \infty$. Second lens $1/s_{i2} = 1/(-20) - 1/(-\infty)$, the object for the second lens is to the right at ∞, that is, $s_{o2} = -\infty$. $s_{i2} = -20$ cm, virtual, 10 cm to the left of first lens.
$$M_T = (-\infty/30)(+20/-\infty) = \frac{2}{3}$$
or from Eq. (5.34)
$$M_T = \frac{30(-20)}{10(30 - 30) - 30(30)} = \frac{2}{3}$$



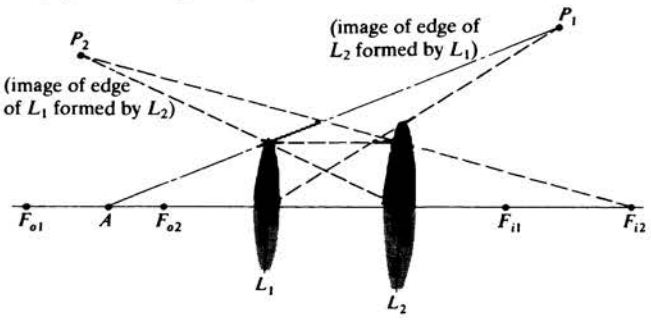
5.41



5.44 The angle subtended by L_1 at S is $\tan^{-1} 3/12 = 14°$. To find the image of the diaphragm in L_1 we use Eq. (5.23): $x_o x_i = f^2$, $(-6)(x_i) = 81$, $x_i = -13.5$ cm, so that the image is 4.5 cm behind L_1. The magnification is $-x_i/f = 13.5/9 = 1.5$, and thus the image (of the edge) of the hole is $(0.5)(1.5) = 0.75$ cm in radius. Hence the angle subtended at S is $\tan^{-1} 0.75/16.5 = 2.6°$. The image of L_2 in L_1 is obtained from $(-4)(x_i) = 81$, $x_i = -20.2$ cm, in other words, the image is 11.2 cm to the right of L_1. $M_T = 20.2/9 = 2.2$; hence the edge of L_2 is imaged 4.4 cm above the axis. Thus its subtended angle at S is $\tan^{-1} 4.4/(12 + 11.2)$ or 9.8°. Accordingly, the diaphragm is the A.S., and the entrance pupil (its image in L_1) has a diameter of 1.5 cm at 4.5 cm behind L_1. The image of the diaphragm in L_2 is the exit pupil. Consequently $\frac{1}{2} + 1/s_i = \frac{1}{3}$ and $s_i = -6$, that is, 6 cm in front of L_2. $M_T = \frac{6}{2} = 3$, so that the exit pupil diameter is 3 cm.



5.45 Either the margin of L_1 or L_2 will be the A.S.; thus, since no lenses are to the left of L_1, either its periphery or P_1 corresponds to the entrance pupil. Beyond (to the left of) point A, L_1 subtends the smallest angle and is the entrance pupil; nearer in (to the right of A), P_1 marks the edge of the entrance pupil. In the former case P_2 is the exit pupil; in the latter (since there are no lenses to the right of L_2) the exit pupil is the edge of L_2 itself.



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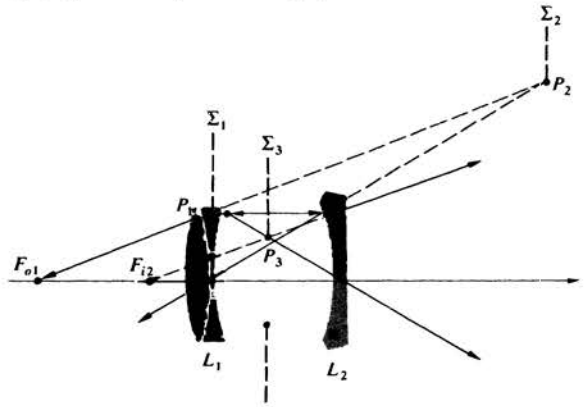
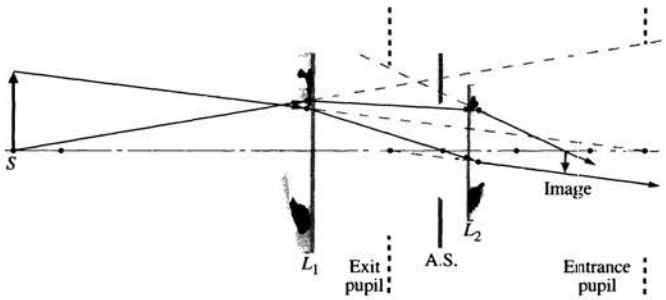
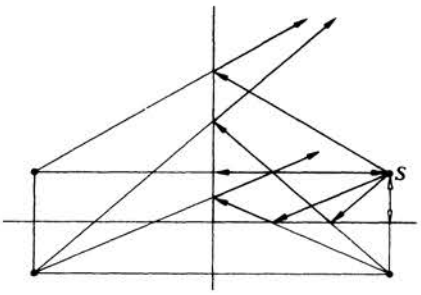
5.46 The A.S. is either the edge of L_1 or L_2. Thus the entrance pupil is either marked by P_1 or P_2. Beyond F_{o1}, P_1 subtends the smaller angle; thus Σ_1 locates the A.S. The image of the A.S. in the lenses to its right, L_2, locates P_3 as the exit pupil.



5.47 Draw the chief ray from the tip to L_1 such that when extended it passes through the center of the entrance pupil. From there it goes through the center of the A.S., and then it bends at L_2 so as to extend through the center of the exit pupil. A marginal ray from S extends to the edge of the entrance pupil, bends at L_1 so it just misses the edge of A.S., and then bends at L_2 so as to pass by the edge of the exit pupil.



5.48



5.49 No—although she might be looking at you.

5.50 The mirror is parallel to the plane of the painting, and so the girl's image should be directly behind her and not off to the right.

5.51 $1/s_o + 1/s_i = -2/R$. Let $R \to \infty$: $1/s_o + 1/s_i = 0$, $s_o = -s_i$, and $M_T = +1$. Image is virtual, same size, and erect.

5.52 From Eq. (5.49), $1/100 + 1/s_i = -2/80$, and so $s_i = -28.5$ cm. Virtual ($s_i < 0$), erect ($M_T > 0$), and minified. (Check with Table 5.5.)

5.55 Image on screen must be real $\therefore$ s_i is +

$$\frac{1}{25} + \frac{1}{100} = -\frac{2}{R}, \quad \frac{5}{100} = -\frac{2}{R}, \qquad R = -40 \text{ cm}$$

5.56 The image is erect and minified. That implies (Table 5.5) a convex spherical mirror.

5.59 To be magnified and erect, the mirror must be concave, and the image virtual; $M_T = 2.0 = s_i/(0.015 \text{ m})$, $s_i = -0.03$ m, and hence $1/f = 1/(0.015 \text{ m}) + 1/(-0.03 \text{ m})$; $f = 0.03$ m and $f = -R/2$; $R = -0.06$ m.

5.60 $M_T = y_i/y_o = -s_i/s_o$, using Eq. (5.50), $s_i = fs_o/(s_o - f)$, and since $f = -R/2$, $M_T = -f/(s_o - f) = -(-R/2)/(s_o + R/2) = R/(2s_o + R)$.

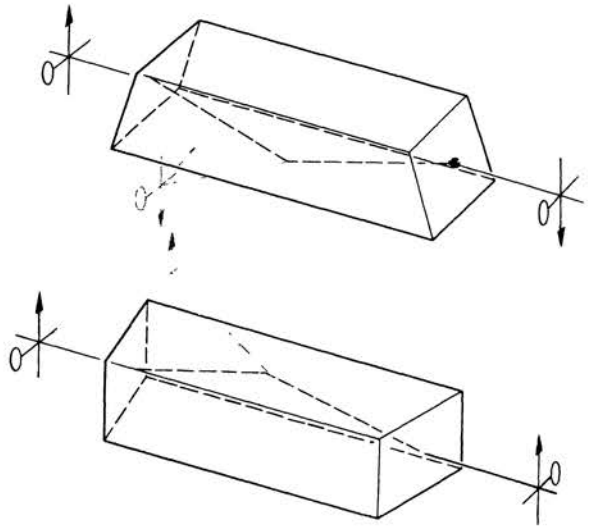
5.63 $M_T = -s_i/25 \text{ cm} = -0.064$; $s_i = 1.6$ cm. $1/25 \text{ cm} + 1/1.6 \text{ cm} = -2/R$, $R = -3.0$ cm.

5.68 $f = -R/2 = 30$ cm, $1/20 + 1/s_i = 1/30$, $1/s_i = 1/30 - 1/20$.

$$s_i = -60 \text{ cm}, \qquad M_T = -s_i/s_o = 60/20 = 3$$

Image is virtual ($s_i < 0$), erect ($M_T > 0$), located 60 cm behind mirror, and 9 inches tall.

5.70 Image rotated through 180°.



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5.71 From Eq. (5.64)

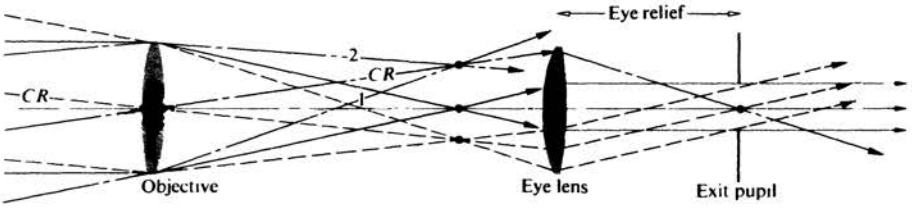
$$\mathrm{NA} = (2.624 - 2.310)^{1/2} = 0.550$$

$$\theta_{\max} = \sin^{-1} 0.550 = 33°22'$$

Maximum acceptance angle is $2\theta_{\max} = 66°44'$. A ray at 45° would quickly leak out of the fiber; in other words, very little energy fails to escape, even at the first reflection.

5.72 Considering Eq. (5.65), $\log 0.5 = -0.30 = -\alpha L/10$, and so $L = 15$ km.

5.73 From Eq. (5.64) NA = 0.232 and $N_m = 9.2 \times 10^2$.



5.75 $M_T = -f/x_o = -1/x_o\mathcal{D}$. for the human eye $\mathcal{D} \approx 58.6$ diopters.

$$x_o = 230000 \times 1.61 = 371 \times 10^3 \text{ km}$$

$$M_T = -1/3.71 \times 10^6(58.6) = 4.6 \times 10^{-11}$$

$$y_i = 2160 \times 1.61 \times 10^3 \times 4.6 \times 10^{-11} = 0.16 \text{ mm}$$

5.77 $1/20 + 1/s_{io} = 1/4, \qquad s_{io} = 5$ m

$$1/0.3 + 1/s_{ie} = 1/0.6, \qquad s_{ie} = -0.6 \text{ m}$$

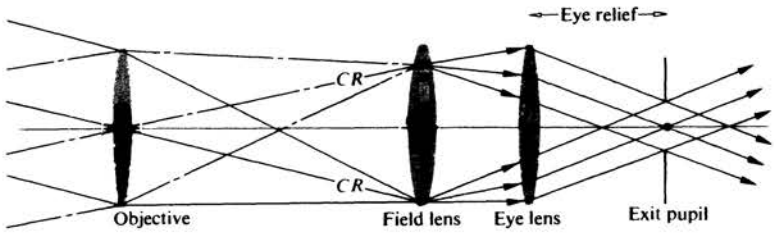
$$M_{To} = -5/10 = -0.5$$

$$M_{Te} = -(-0.6)/0.5 = +1.2$$

$$M_{To}M_{Te} = -0.6$$

5.81 Ray 1 in the figure above misses the eye-lens, and there is, therefore, a decrease in the energy arriving at the corresponding image point. This is vignetting.

5.82 Rays that would have missed the eye-lens in the previous problem are made to pass through it by the field-lens. Note how the field-lens bends the chief rays a bit so that they cross the optical axis slightly closer to the eye-lens, thereby moving the exit pupil and shortening the eye relief. (For more on the subject, see *Modern Optical Engineering*, by Smith.)



5.86 $\mathcal{D}_l - \dfrac{\mathcal{D}_c}{1 + \mathcal{D}_c d} = \dfrac{3.2D}{1 + (3.2D)(0.017 \text{ m})} = +3.03D$

or to two figures $+3.0D$. $f_l = 0.330$ m, and so the far point is 0.330 m − 0.017 m = 0.313 m behind the eye lens. For the contact lens $f_c = 1/3.2 = 0.313$ m. Hence the far point at 0.31 m is the same for both, as it indeed must be.

5.88

(a) The intermediate image-distance is obtained from the lens formula applied to the objective;

$$\frac{1}{27 \text{ mm}} + \frac{1}{s_i} = \frac{1}{25 \text{ mm}}$$

and $s_i = 3.38 \times 10^2$ mm. This is the distance from the objective to the intermediate image, to which must be added the focal length of the eyepiece to get the lens separation; 3.38×10^2 mm + 25 mm = 3.6×10^2 mm.

(b) $M_{To} = -s_i/s_o = -3.38 \times 10^2 \text{ mm}/27 \text{ mm} = -12.5\times$, while the eyepiece has a magnification of $d_o\mathcal{D} = (254 \text{ mm})(1/25 \text{ mm}) = 10.2\times$. Thus the total magnification is MP = $(-12.5)(10.2) = -1.3 \times 10^2$; the minus sign just means the image is inverted.

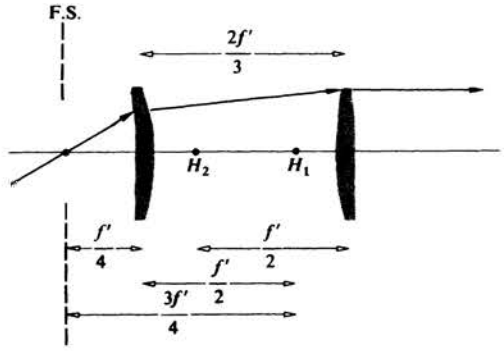
Chapter 6

6.2 From Eq. (6.8),

$$1/f = 1/f' + 1/f' - d/f'f' = 2/f' - 2/3f', \qquad f = 3f'/4$$

From Eq. (6.9), $\overline{H_{11}H_1} = (3f'/4)(2f'/3)/f' = f'/2$

From Eq. (6.10), $\overline{H_{22}H_2} = -(3f'/4)(2f'/3)/f' = -f'/2$



6.3 From Eq. (6.2), $1/f = 0$ when $-(1/R_1 - 1/R_2) = (n_l - 1)d/n_lR_1R_2$. Thus $d = n_l(R_1 - R_2)/(n_l - 1)$.

6.4 $1/f = 0.5[1/6 - 1/10 + 0.5(3)/1.5(6)10]$

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$= 0.5[10/60 - 6/60 + 1/60]$; $f = +24$

$h_1 = -24(0.5)(3)/10(1.5) = -2.4$

$h_2 = -24(0.5)(3)/6(1.5) = -4$

6.6 $f = \frac{1}{2}nR/(n-1)$; $h_1 = +R$, $h_2 = -R$

6.10 $f = 29.6 + 0.4 = 30$ cm; $s_o = 49.8 + 0.2 = 50$ cm; $1/50 + 1/s_i = 1/30$ cm. $s_i = 75$ cm from H_2 and 74.6 cm from the back face.

6.12 From Eq. (6.2),

$$1/f = \tfrac{1}{2}[(1/4.0) - (1/-15) + \tfrac{1}{2}(4.0)/(3/2)(4.0)(-15)]$$
$$= 0.147 \quad \text{and} \quad f = 6.8 \text{ cm.}$$

$h_1 = -(6.8)\frac{1}{2}(4.0)/(-15)(3/2) = +0.60$ cm, while $h_2 = -2.3$. To find the image $1/(100.6) + 1/s_i = 1/(6.8)$; $s_i = 7.3$ cm or 5 cm from the back face of the lens.

6.18 $h_1 = n_{i1}(1 - a_{11})/-a_{12} = (\mathcal{D}_2 d_{21}/n_{t1})f$

$= -(n_{t1} - 1)d_{21}f/R_2 n_{t1}$

from Eq. (5.64) where $n_{t1} = n_l$;

$$h_2 = n_{t2}(a_{22} - 1)/-a_{12}$$
$$= -(\mathcal{D}_1 d_{21}/n_{t1})f \text{ from Eq. (5.70)}$$
$$= -(n_{i1} - 1)d_{21}f/R_1 n_{t1}$$

6.19 $\mathcal{A} = \mathcal{R}_2\mathcal{T}_{21}\mathcal{R}_1$, but for the planar surface

$$\mathcal{R}_2 = \begin{bmatrix} 1 & -\mathcal{D}_2 \\ 0 & 1 \end{bmatrix}$$

and $\mathcal{D}_2 = (n_{t1} - 1)/(-R_2)$ but $R_2 = \infty$

$$\mathcal{R}_2 = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$

which is the unit matrix, hence $\mathcal{A} = \mathcal{T}_{21}\mathcal{R}_1$.

6.20 $\mathcal{D}_1 = (1.5 - 1)/0.5 = 1$

and $\mathcal{D}_2 = (1.5 - 1)/-(-0.25) = 2$

$$\mathcal{A} = \begin{bmatrix} 1 - 2(0.3)/1.5 & -1 + 2(1)(0.3)/(1.5 - 2) \\ 0.3/1.5 & -1(0.3)/1.5 + 1 \end{bmatrix}$$

$$= \begin{bmatrix} 0.6 & -2.6 \\ 0.2 & 0.8 \end{bmatrix}$$

$$|\mathcal{A}| = 0.6(0.8) - (0.2)(-2.6) = 0.48 + 0.52 = 1$$

6.25 See E. Slayter, *Optical Methods in Biology*. $\overline{PC}/\overline{CA} = (n_1/n_2)R/R = n_1/n_2$, while $\overline{CA}/\overline{P'C} = n_1/n_2$. Therefore triangles ACP and ACP' are similar; using the sine law

$$\frac{\sin \measuredangle PAC}{\overline{PC}} = \frac{\sin \measuredangle APC}{\overline{CA}}$$

or

$$n_2 \sin \measuredangle PAC = n_1 \sin \measuredangle APC$$

but $\theta_i = \measuredangle PAC$, thus $\theta_t = \measuredangle APC = \measuredangle P'AC$, and the refracted ray appears to come from P'.

6.26 From Eq. (5.6), let $\cos\varphi = 1 - \varphi^2/2$; then

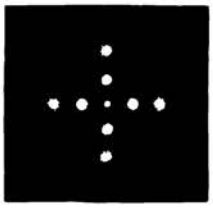
$$\ell_o = [R^2 + (s_o + R)^2 - 2R(s_o + R) + R(s_o + R)\varphi^2]^{1/2}$$
$$\ell_o^{-1} = [s_o^2 + R(s_o + R)\varphi^2]^{-1/2}$$
$$\ell_i^{-1} = [s_i^2 - R(s_i - R)\varphi^2]^{-1/2}$$

where the first two terms of the binomial series are used,

$$\ell_o^{-1} \approx s_o^{-1} - (s_o + R)h^2/2s_o^3R \quad \text{where } \varphi \approx h/R,$$
$$\ell_i^{-1} \approx s_i^{-1} + (s_i - R)h^2/2s_i^3R$$

Substituting into Eq. (5.5) leads to Eq. (6.40).

6.27



Chapter 7

7.1 $E_0^2 = 36 + 64 + 2 \cdot 6 \cdot 8 \cos \pi/2 = 100$, $E_0 = 10$; $\tan\alpha = \frac{8}{6}$, $\alpha = 53.1° = 0.93$ rad.

$$E = 10 \sin(120\pi t + 0.93)$$

7.5 $\dfrac{1 \text{ m}}{500 \text{ nm}} = 0.2 \times 10^7 = 2\,000\,000$ waves

$$\text{In the glass } \frac{0.05}{\lambda_0/n} = \frac{0.05(1.5)}{500 \text{ nm}} = 1.5 \times 10^5$$
$$\text{in air } \frac{0.95}{\lambda_0} = 0.19 \times 10^7$$

total 2 050 000 waves.

$OPD = [(1.5)(0.05) + (1)(0.95)] - (1)(1)$

$OPD = 1.025 - 1.000 = 0.025$ m

$$\frac{\Lambda}{\lambda_0} = \frac{0.025}{500 \text{ nm}} = 5 \times 10^4 \text{ waves}$$

7.8 $E = E_1 + E_2 = E_{01}\{\sin[\omega t - k(x + \Delta x) + \sin(\omega t - kx)\}$

Since $\sin\beta + \sin\gamma = 2\sin\frac{1}{2}(\beta + \gamma)\cos\frac{1}{2}(\beta - \gamma)$

$$E = 2E_{01}\cos\frac{k\Delta x}{2}\sin\left[\omega t - k\left(x + \frac{\Delta x}{2}\right)\right]$$

7.9 $E = E_0 \text{Re}[e^{i(kx+\omega t)} - e^{i(kx-\omega t)}]$

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$$= E_0 \mathrm{Re}[e^{ikx}(e^{i\omega t} - e^{-i\omega t})]$$
$$= E_0 \mathrm{Re}[e^{ikx} 2i \sin \omega t]$$
$$= E_0 \mathrm{Re}[2i \cos kx \sin \omega t - 2 \sin kx \sin \omega t]$$

and $E = -2E_0 \sin kx \sin \omega t$. Standing wave with node at $x = 0$.

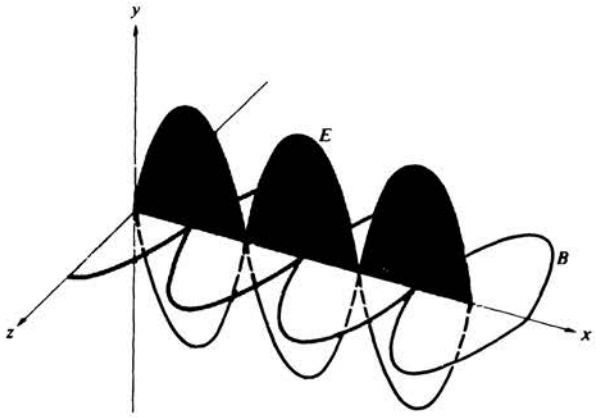
7.11
$$\frac{\partial E}{\partial x} = -\frac{\partial B}{\partial t}$$

Integrate to get

$$B(x, t) = -\int \frac{\partial E}{\partial x} dt = -2E_0 k \cos kx \int \cos \omega t \, dt$$
$$= -\frac{2E_0 k}{\omega} \cos kx \sin \omega t$$

But $E_0 k/\omega = E_0/c = B_0$; thus

$$B(x, t) = -2B_0 \cos kx \sin \omega t$$



7.18 $E = E_0 \cos \omega_c t + E_0 \alpha \cos \omega_m t \cos \omega_c t$

$$= E_0 \cos \omega_c t + \frac{E_0 \alpha}{2} [\cos (\omega_c - \omega_m)t + \cos (\omega_c + \omega_m)t]$$

Audible range $\nu_m = 20$ Hz to 20×10^3 Hz. Maximum modulation frequency $\nu_m(\max) = 20 \times 10^3$ Hz.

$$\nu_c - \nu_m(\max) \le \nu \le \nu_c + \nu_m(\max)$$
$$\Delta\nu = 2\nu_m(\max) = 40 \times 10^3 \text{ Hz}$$

7.19 $v = \omega/k = ak, \qquad v_g = d\omega/dk = 2ak = 2v$

7.22
$$v = \sqrt{\frac{g\lambda}{2\pi}} = \sqrt{g/k}$$
$$v_g = v + k\frac{dv}{dk} \qquad [7.38]$$
$$\frac{dv}{dk} = -\frac{1}{2k}\sqrt{\frac{g}{k}} = -\frac{v}{2k}$$
$$v_g = v/2$$

7.24 $v_g = v + k\dfrac{dv}{dk}$ and $\dfrac{dv}{dk} = \dfrac{dv}{d\omega}\dfrac{d\omega}{dk} = v_g \dfrac{dv}{d\omega}$

Since $v = c/n$, $\dfrac{dv}{d\omega} = \dfrac{dv}{dn}\dfrac{dn}{d\omega} = -\dfrac{c}{n^2}\dfrac{dn}{d\omega}$

$$v_g = v - \frac{v_g ck}{n^2}\frac{dn}{d\omega} = \frac{v}{1 + (ck/n^2)(dn/d\omega)} = \frac{c}{n + \omega(dn/d\omega)}$$

7.30 $\omega >> \omega_i, \qquad n^2 = 1 - \dfrac{Nq_e^2}{\omega^2 \epsilon_0 m_e} \sum f_i = 1 - \dfrac{Nq_e^2}{\omega^2 \epsilon_0 m_e}$

Using the binomial expansion, we have

$$(1 - x)^{1/2} \approx 1 - \frac{1}{2}x \quad \text{for } x << 1$$
$$n = 1 - Nq_e^2/\omega^2 \epsilon_0 m_e 2, \qquad dn/d\omega = Nq_e^2/\epsilon_0 m_e \omega^3$$
$$v_g = \frac{c}{n + \omega(dn/d\omega)}$$
$$= \frac{c}{1 - Nq_e^2/\omega^2 \epsilon_0 m_e 2 + Nq_e^2/\epsilon_0 m_e \omega^2}$$
$$= \frac{c}{1 + Nq_e^2/\epsilon_0 m_e \omega^2 2}$$

and $v_g < c$,

$$v = c/n = \frac{c}{1 - Nq_e^2/\epsilon_0 m_e \omega^2 2}$$

Binomial expansion

$$(1 - x)^{-1} \approx 1 + x, \qquad x << 1$$
$$v = c[1 + Nq_e^2/e_0 m_e \omega^2 2]; \qquad v v_g = c^2$$

7.32 $\displaystyle\int_0^\lambda \sin akx \sin bkx \, dx$

$$= \frac{1}{2k}\left[\int_0^\lambda \cos [(a - b)kx]k \, dx - \int_0^\lambda \cos [(a + b)kx]k \, dx\right]$$
$$= \frac{1}{2k}\frac{\sin(a - b)kx}{a - b}\bigg|_0^\lambda - \frac{1}{2k}\frac{\sin (a + b)kx}{a + b}\bigg|_0^\lambda$$
$$= 0 \quad \text{if } a \ne b$$

Whereas if $a = b$

$$\int_0^\lambda \sin^2 akx \, dx = \frac{1}{2k}\int_0^\lambda (1 + \cos 2akx)k \, dx = \frac{\lambda}{2}$$

The other integrals are similar.

7.33 Even function, therefore $B_m = 0$.

$$A_0 = \frac{2}{\lambda}\int_{-\lambda/a}^{\lambda/a} dx = \frac{2}{\lambda}\left(\frac{\lambda}{a} + \frac{\lambda}{a}\right) = \frac{4}{a}$$

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$$A_m = \frac{2}{\lambda}\int_{-\lambda/a}^{\lambda/a} (1)\cos mkx\,dx$$

$$A_m = \frac{2}{mk\lambda}\sin mkx\Big]_{-\lambda/a}^{\lambda/a}$$

$$A_m = \frac{2}{m\pi}\sin\frac{m2\pi}{a}$$

7.37

$$f'(x) = \frac{1}{\pi}\int_0^a E_0 L\frac{\sin kL/2}{kL/2}\cos kx\,dk$$

$$= \frac{E_0 L}{\pi 2}\int_0^b \frac{\sin(kL/2 + kx)}{kL/2}\,dk + \frac{E_0 L}{\pi 2}\int_0^b \frac{\sin(kL/2 - kx)}{kL/2}\,dk$$

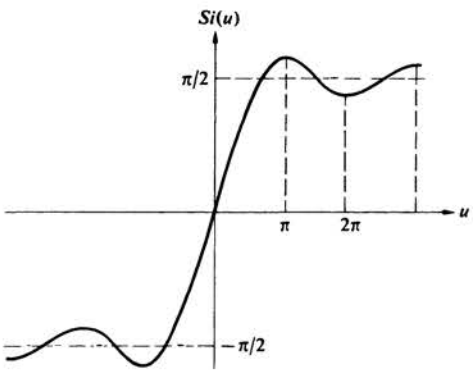
Let $kL/2 = w$, $(L/2)\,dk = dw$, $kx = wx'$.

$$f'(x) = \frac{E_0}{\pi}\int_0^b \frac{\sin(w + wx')}{w}\,dw + \frac{E_0}{\pi}\int_0^b \frac{\sin(w - wx')}{w}\,dw$$

where $b = aL/2$. Let $w + wx' = t$, $dw/w = dt/t$. $0 \le w \le b$ and $0 \le t \le (x' + 1)b$. Let $w - wx' = -t$ in the other integral. $0 \le w \le b$ and $0 \le t \le (x' - 1)b$.

$$f'(x) = \frac{E_0}{\pi}\int_0^{(x'+1)b}\frac{\sin t}{t}\,dt - \frac{E_0}{\pi}\int_0^{(x'-1)b}\frac{\sin t}{t}\,dt$$

$$f'(x) = \frac{E_0}{\pi}\,\mathrm{Si}\,[b(x' + 1)] - \frac{E_0}{\pi}\,\mathrm{Si}\,[b(x' - 1)], \qquad x' = 2x/L$$



7.38 By analogy with Eq. (7.61),

$$A(\omega) = \frac{\Delta t}{2}E_0\,\mathrm{sinc}\,(\omega_p - \omega)\frac{\Delta t}{2}$$

From Table 1 (p. 653) sinc $(\pi/2) = 63.7\%$. Not quite 50% actually,

$$\mathrm{sinc}\left(\frac{\pi}{1.65}\right) = 49.8\%$$

$$\left|(\omega_p - \omega)\frac{\Delta t}{2}\right| < \frac{\pi}{2} \quad \text{or} \quad -\frac{\pi}{\Delta t} < (\omega_p - \omega) < \frac{\pi}{\Delta t}$$

Thus appreciable values of $A(\omega)$ lie in a range $\Delta\omega \sim 2\pi/\Delta t$ and $\Delta\nu\,\Delta t \sim 1$. The power spectrum is proportional to $A^2(\omega)$, and [sinc $(\pi/2)]^2 = 40.6\%$.

7.39 $\Delta l_c = c\,\Delta t_c$, $\Delta l_c \approx c/\Delta\nu$. But $\Delta\omega/\Delta k_0 = \bar{\omega}/\bar{k}_0 = c$; thus $|\Delta\nu/\Delta\lambda_0| = \bar{\nu}/\bar{\lambda}_0$,

$$\Delta l_c \approx \frac{c\bar{\lambda}_0}{\Delta\lambda_0\bar{\nu}} \qquad \Delta l_c \approx \bar{\lambda}_0^2/\Delta\lambda_0$$

Or try using the uncertainty principle:

$$\Delta l \approx \frac{h}{\Delta p} \quad \text{where } p = h/\lambda \text{ and } \Delta\lambda_0 << \bar{\lambda}_0$$

7.40

$$\Delta l_c = c\,\Delta t_c = 3\times 10^8\ \mathrm{m/s}\ 10^{-8}\ \mathrm{s} = 3\ \mathrm{m}$$

$$\Delta\lambda_0 \sim \lambda_0^2/\Delta l_c = (500\times 10^{-9}\ \mathrm{m})^2/3\ \mathrm{m}$$

$$\Delta\lambda_0 \sim 8.3\times 10^{-14}\ \mathrm{m} = 8.3\times 10^{-5}\ \mathrm{nm}$$

$$\Delta\lambda_0/\bar{\lambda}_0 = \Delta\nu/\bar{\nu} = 8.3\times 10^{-5}/500 = 1.6\times 10^{-7}$$

$$\approx 1 \text{ part in } 10^7$$

7.41 $\Delta\nu = 54\times 10^3$ Hz

$$\Delta\nu/\bar{\nu} = \frac{(54\times 10^3)(10\,600\times 10^{-9}\ \mathrm{m})}{(3\times 10^8\ \mathrm{m/s})}$$

$$= 1.91\times 10^{-9}$$

$$\Delta l_c = c\Delta t_c \approx c/\Delta\nu$$

$$\Delta l_c \approx \frac{(3\times 10^8\ \mathrm{m/s})}{(54\times 10^3\ \mathrm{Hz})} = 5.55\times 10^3\ \mathrm{m}$$

7.43 $\Delta l_c = c\,\Delta t_c = 3\times 10^8\times 10^{-10} = 3\times 10^{-2}$ m

$$\Delta\nu \approx 1/\Delta t_c = 10^{10}\ \mathrm{Hz}$$

$$\Delta\lambda_0 \approx \bar{\lambda}_0^2/\Delta l_c \text{ (see Problem 7.39)}$$

$$= (632.8\ \mathrm{nm})^2/3\times 10^{-2}\ \mathrm{m} = 0.013\ \mathrm{nm}$$

$$\Delta\nu = 10^{15}\ \mathrm{Hz},\ \Delta l_c = c\times 10^{-15} = 300\ \mathrm{nm}$$

$$\Delta\lambda_0 \approx \bar{\lambda}_0^2/\Delta l_c = 1334.78\ \mathrm{nm}$$

Chapter 8

8.1

(a) $\vec{\mathbf{E}} = \hat{\mathbf{i}}E_0\cos(kz - \omega t) + \hat{\mathbf{j}}E_0\cos(kz - \omega t + \pi)$. Equal amplitudes, E_y lags E_x by π. Therefore $\mathcal{P}$-state at 135° or −45°.

(b) $\vec{\mathbf{E}} = \hat{\mathbf{i}}E_0\cos(kz - \omega t - \pi/2) + \hat{\mathbf{j}}E_0\cos(kz - \omega t + \pi/2)$. Equal amplitudes, E_y lags E_x by π. Therefore same as (a).

(c) E_x leads E_y by $\pi/4$. They have equal amplitudes. Therefore it is an ellipse tilted at +45° and is left-handed.

(d) E_y leads E_x by $\pi/2$. They have equal amplitudes. Therefore it is an $\mathcal{R}$-state.

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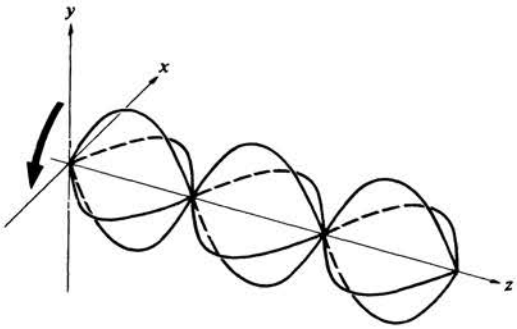
8.2 $\vec{\mathbf{E}}_x = \hat{\mathbf{i}} \cos \omega t, \qquad \vec{\mathbf{E}}_y = \hat{\mathbf{j}} \sin \omega t$

Left-handed circular standing wave.



8.3 $\vec{\mathbf{E}}_{\mathcal{R}} = \hat{\mathbf{i}} E_0 \cos (kz - \omega t) + \hat{\mathbf{j}} E_0 \sin (kz - \omega t)$

$$\vec{\mathbf{E}}_{\mathcal{L}} = \hat{\mathbf{i}} E_0' \cos (kz - \omega t) - \hat{\mathbf{j}} E_0' \sin (kz - \omega t)$$

$$\vec{\mathbf{E}} = \vec{\mathbf{E}}_{\mathcal{R}} + \vec{\mathbf{E}}_{\mathcal{L}} = \hat{\mathbf{i}} (E_0 + E_0') \cos (kz - \omega t) + \hat{\mathbf{j}} (E_0 - E_0') \sin (kz - \omega t).$$

Let $E_0 + E_0' = E_{0x}''$ and $E_0 - E_0' = E_{0y}''$; then $\vec{\mathbf{E}} = \hat{\mathbf{i}} E_{0x}'' \cos (kz - \omega t) + \hat{\mathbf{j}} E_{0y}'' \sin (kz - \omega t)$. From Eqs. (8.11) and (8.12) it is clear that we have an ellipse where $\varepsilon = -\pi/2$ and $\alpha = 0$.

8.4 $E_{0y} = E_0 \cos 25°$; $E_{0z} = E_0 \sin 25°$;

$$\vec{\mathbf{E}}(x, t) = (0.91\hat{\mathbf{j}} + 0.42\hat{\mathbf{k}}) E_0 \cos (kx - \omega t + \tfrac{1}{2}\pi)$$

8.6 $\vec{\mathbf{E}} = E_0[\hat{\mathbf{j}} \sin (kx - \omega t) - \hat{\mathbf{k}} \cos (kx - \omega t)]$

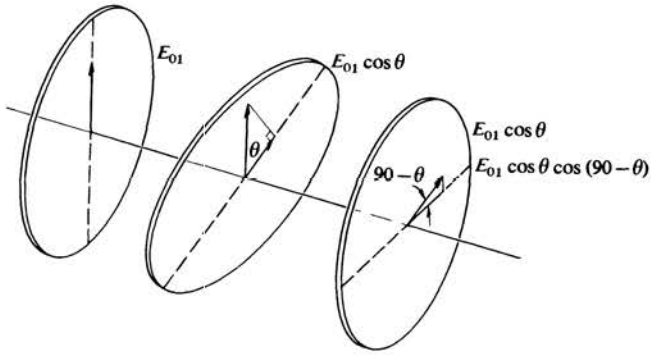
8.10 In natural light each filter passes 32% of the incident beam. Half of the incoming flux density is in the form of a $\mathcal{P}$-state parallel to the extinction axis, and effectively none of this emerges. Thus, 64% of the light parallel to the transmission axis is transmitted. In the present problem $32\% I_i$ enters the second filter, and $64\%\ (32\% I_i) = 21\% I_i$ leaves it.

8.21 From the figure, it follows that

$$I = \tfrac{1}{2} E_{01}^2 \sin^2 \theta \cos^2 \theta = \frac{E_{01}^2}{8} (1 - \cos 2\theta)(1 + \cos 2\theta)$$

$$= \frac{E_{01}^2}{8} (1 - \cos^2 2\theta) = \frac{E_{01}^2}{8} [1 - (\tfrac{1}{2} \cos 4\theta + \tfrac{1}{2})]$$

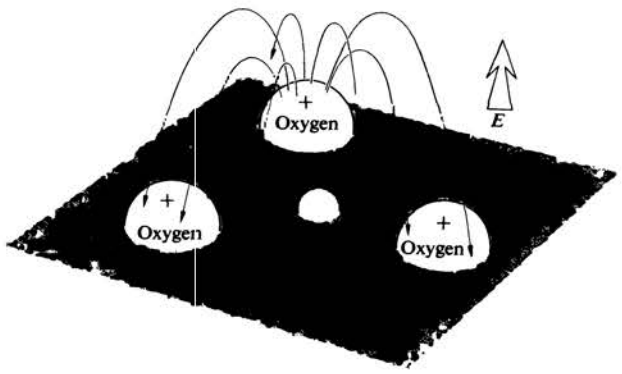
$$= \frac{E_{01}^2}{16} (1 - \cos 4\theta) = \frac{I_1}{8} (1 - \cos 4\theta) \qquad \theta = \omega t$$

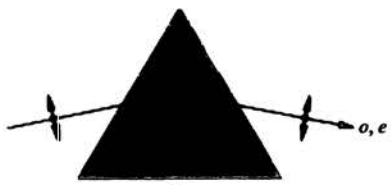


8.22 No. The crystal performs as if it were two oppositely oriented specimens in series. Two similarly oriented crystals in series would behave like one thick specimen and thus separate the *o*- and *e*-rays even more.

8.24 Light scattered from the paper passes through the polaroids and becomes linearly polarized. Light from the upper left filter has its $\vec{\mathbf{E}}$-field parallel to the principal section (which is diagonal across the second and fourth quadrants) and is therefore an *e*-ray. Notice how the letters *P* and *T* are shifted downward in an *extraordinary* fashion. The lower right filter passes an *o*-ray so that the *C* is undeviated. Note that the ordinary image is closer to the blunt corner.

8.25 (a) and (c) are two aspects of the previous problem. (b) shows double refraction because the polaroid's axis is at roughly 45° to the principal section of the crystal. Thus both an *o*- and an *e*-ray will exist.





(a)

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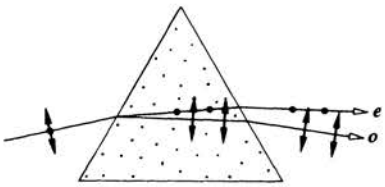
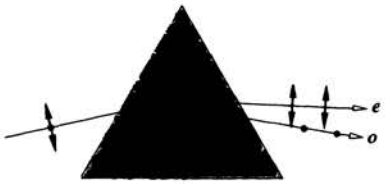
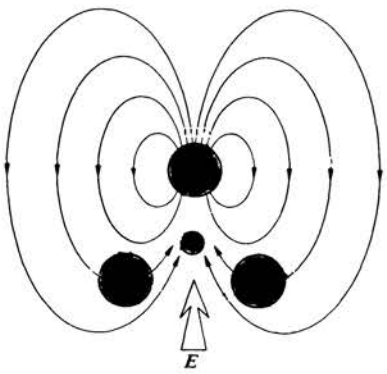


(b)



(c)

8.26 When $\vec{\mathbf{E}}$ is perpendicular to the CO_3 plane, the polarization will be less than when it is parallel. In the former case, the field of each polarized oxygen atom tends to reduce the polarization of its neighbors. In other words, the induced field, as shown in the figure, is down while $\vec{\mathbf{E}}$ is up. When $\vec{\mathbf{E}}$ is in the carbonate plane, two dipoles reinforce the third and vice versa. A reduced polarizability leads to a lower dielectric constant, a lower refractive index, and a higher speed. Thus $v_{\parallel} > v_{\perp}$.



8.34 $n_o = 1.6584$, $n_e = 1.4864$. Snell's Law:

$$\sin\theta_i = n_o \sin\theta_{to} = 0.766$$
$$\sin\theta_i = n_e \sin\theta_{te} = 0.766$$
$$\sin\theta_{to} \approx 0.463, \qquad \theta_{to} \approx 27°35'$$
$$\sin\theta_{te} \approx 0.516, \qquad \theta_{te} \approx 31°4'$$
$$\Delta\theta \approx 3°29'$$

8.36 Calcite $n_o > n_e$. Two spectra will be visible when (b) or (c) is used in a spectrometer. The indices are computed in the usual way, using

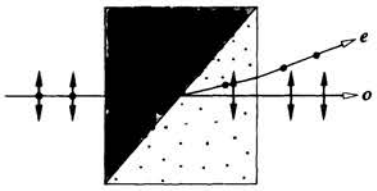
$$n = \frac{\sin\frac{1}{2}(\alpha + \delta_m)}{\sin\frac{1}{2}\alpha}$$

where δ_m is the angle of minimum deviation of either beam.

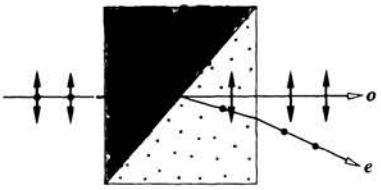
8.37 E_x leads E_y by $\pi/2$. They were initially in phase and $E_x > E_y$. Therefore the wave is left-handed, elliptical, and horizontal.

8.38 $\sin\theta_c = \dfrac{n_{\text{balsam}}}{n_0} = \dfrac{1.55}{1.658} = 0.935;\ \theta_c \sim 69°$

8.40



(a) Calcite



(b) Quartz

(c) Undesired energy in the form of one of the $\mathcal{P}$-states can be disposed of without local heating problems.

(d) The Rochon transmits an undeviated beam (the o-ray), which is therefore achromatic as well.

8.45
$$\Delta\varphi = \frac{2\pi}{\lambda_0} d\,\Delta n$$

but $\Delta\varphi = (1/4)(2\pi)$ because of the fringe shift. Therefore $\Delta\varphi = \pi/2$ and

$$\frac{\pi}{2} = \frac{2\pi\, d\,(0.005)}{589.3 \times 10^{-9}}$$

$$d = \frac{589.3 \times 10^{-9}}{2(10^{-2})} = 2.94 \times 10^{-5}\ \text{m}$$

8.46 The $\mathcal{R}$-state incident on the glass screen drives the electrons in circular orbits, and they reradiate reflected circular light whose $\vec{\mathbf{E}}$-field rotates in the same direction as that of the incoming beam. But

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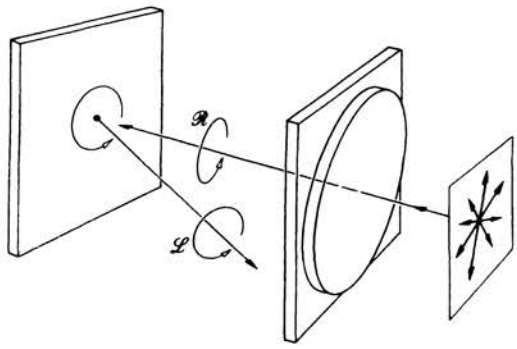
the propagation direction has been reversed on reflection, so that although the incident light is in an $\mathcal{R}$-state, the reflected light is left-handed. It will therefore be completely absorbed by the right-circular polarizer. This is illustrated in the figure below.



8.47 Yes. If the amplitudes of the $\mathcal{P}$-states differ. The transmitted beam, in a pile-of-plates polarizer, especially for a small pile.

8.49 Place the photoelastic material between circular polarizers with both retarders facing it (as in Fig. 8.51). Under circular illumination no orientation of the stress axes is preferred over any other, and they will thus all be indistinguishable. Only the birefringence will have an effect, and so the isochromatics will be visible. If the two polarizers are different, that is, one an $\mathcal{R}$, the other an $\mathcal{L}$, regions where Δn leads to $\Delta\varphi = \pi$ will appear bright. If they are the same, such regions appear dark.

8.51 $V_{\lambda/2} = \lambda_0/2n_0^3 r_{63}$ [8.44]

$$= 550 \times 10^{-9}/2(1.58)^3 5.5 \times 10^{-12}$$

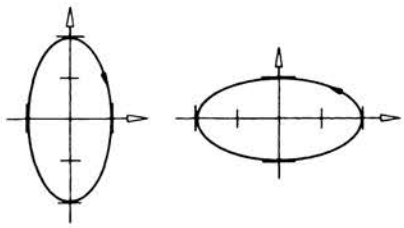
$$= 10^5/2(3.94) = 12.7 \text{ kV}$$

8.53 $\vec{\mathbf{E}}_1 \cdot \vec{\mathbf{E}}_2^* = 0,\ \vec{\mathbf{E}}_2 = \begin{bmatrix} e_{21} \\ e_{22} \end{bmatrix}$

$$\vec{\mathbf{E}}_1 \cdot \vec{\mathbf{E}}_2^* = (1)\,(e_{21})^* + (-2i)(e_{22})^* = 0$$

$$\vec{\mathbf{E}}_2 = \begin{bmatrix} 2 \\ i \end{bmatrix}$$

$\vec{\mathbf{E}}_1$ is $\qquad\qquad$ $\vec{\mathbf{E}}_2$ is



8.61

$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \\ 0 & -1 & 0 & 0 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

8.63

$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & -1 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & -1 \\ 0 & 0 & 1 & 0 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{bmatrix}$$

$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{bmatrix} \begin{bmatrix} 1 \\ 0 \\ 0 \\ 1 \end{bmatrix} = \begin{bmatrix} 1 \\ 0 \\ 0 \\ -1 \end{bmatrix}$$

$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{bmatrix} \begin{bmatrix} 1 \\ 0 \\ 0 \\ -1 \end{bmatrix} = \begin{bmatrix} 1 \\ 0 \\ 0 \\ 1 \end{bmatrix}$$

$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & -1 & 0 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & -1 & 0 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{bmatrix}$$

8.64

$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & -1 \\ 0 & 0 & 1 & 0 \end{bmatrix} \tfrac{1}{2} \begin{bmatrix} 1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \\ 1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} = \tfrac{1}{2} \begin{bmatrix} 1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 1 & 0 & 1 & 0 \end{bmatrix}$$

$$\tfrac{1}{2} \begin{bmatrix} 1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 1 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \end{bmatrix} = \tfrac{1}{2} \begin{bmatrix} 1 \\ 0 \\ 0 \\ 1 \end{bmatrix}$$

$$\tfrac{1}{2} \begin{bmatrix} 1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 1 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} 1 \\ 0 \\ 0 \\ 1 \end{bmatrix} = \tfrac{1}{2} \begin{bmatrix} 1 \\ 0 \\ 0 \\ 1 \end{bmatrix}$$

$$\tfrac{1}{2} \begin{bmatrix} 1 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 \\ 0 \\ 0 \\ 1 \end{bmatrix} = \tfrac{1}{2} \begin{bmatrix} 1 \\ 0 \\ 0 \\ 1 \end{bmatrix}$$

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$$\frac{1}{2}\begin{bmatrix}1&0&1&0\\0&0&0&0\\0&0&0&0\\1&0&1&0\end{bmatrix}\begin{bmatrix}1\\0\\0\\-1\end{bmatrix}=\frac{1}{2}\begin{bmatrix}1\\0\\0\\1\end{bmatrix}$$

$$\frac{1}{2}\begin{bmatrix}1&0&0&1\\0&0&0&0\\0&0&0&0\\1&0&0&1\end{bmatrix}\begin{bmatrix}1\\0\\0\\-1\end{bmatrix}=\begin{bmatrix}0\\0\\0\\0\end{bmatrix}$$

8.66
$$\begin{bmatrix}te^{i\varphi}&0\\0&te^{i\varphi}\end{bmatrix}$$

where a phase increment of φ is introduced into both components as a result of traversing the plate.

$$\begin{bmatrix}1&0\\0&1\end{bmatrix}\qquad\begin{bmatrix}0&0\\0&0\end{bmatrix}$$

8.67
$$\begin{bmatrix}t^2&0&0&0\\0&t^2&0&0\\0&0&t^2&0\\0&0&0&t^2\end{bmatrix}\qquad\begin{bmatrix}1&0&0&0\\0&0&0&0\\0&0&0&0\\0&0&0&0\end{bmatrix}$$

8.68
$$V=\frac{I_p}{I_p+I_u}=\frac{(\mathcal{S}_1^2+\mathcal{S}_2^2+\mathcal{S}_3^2)^{1/2}}{\mathcal{S}_0}$$

$$I_p=(\mathcal{S}_1^2+\mathcal{S}_2^2+\mathcal{S}_3^2)^{1/2};\qquad I-I_p=I_u$$

$$\mathcal{S}_0-(\mathcal{S}_1^2+\mathcal{S}_2^2+\mathcal{S}_3^2)^{1/2}=I_u$$

$$\begin{bmatrix}4\\0\\0\\0\end{bmatrix}+\begin{bmatrix}1\\0\\0\\1\end{bmatrix}=\begin{bmatrix}5\\0\\0\\1\end{bmatrix}$$

$$5-(0+0+1)^{1/2}=I_u$$

8.70

(a)
$$\begin{bmatrix}\cos^2\alpha&\cos\alpha\sin\alpha\\\cos\alpha\sin\alpha&\sin^2\alpha\end{bmatrix}\begin{bmatrix}\cos\theta\\\sin\theta\end{bmatrix}=$$

$$\begin{bmatrix}\cos^2\alpha\cos\theta+\cos\alpha\sin\alpha\sin\theta\\\cos\alpha\sin\alpha\cos\theta+\sin^2\alpha\sin\theta\end{bmatrix}=\cos(\theta-\alpha)\begin{bmatrix}\cos\alpha\\\sin\alpha\end{bmatrix}$$

(b) Emerging beam is polarized at angle α to the horizontal and its amplitude is reduced by a factor $\cos(\theta-\alpha)$. This is exactly what an ideal linear polarizer would do if its transmission axis were oriented at α to the horizontal (recall Malus's law).

(c) (For example). Construct the Jones matrix for crossed polarizers. Let the second polarizer be at angle $\alpha-90°$ so that $\cos\alpha$ is replaced by $\sin\alpha$ and $\sin\alpha$ by $-\cos\alpha$. The Jones matrix for the combination is then

$$\begin{bmatrix}\cos^2\alpha&\cos\alpha\sin\alpha\\\cos\alpha\sin\alpha&\sin^2\alpha\end{bmatrix}\begin{bmatrix}\sin^2\alpha&\sin\alpha\cos\alpha\\\sin\alpha\cos\alpha&\cos^2\alpha\end{bmatrix}=$$

$$\begin{bmatrix}0&0\\0&0\end{bmatrix}\ \text{(the null matrix!)}$$

Chapter 9

9.1 $\vec{\mathbf{E}}_1\cdot\vec{\mathbf{E}}_2=\frac{1}{2}(\vec{\mathbf{E}}_1e^{-i\omega t}+\vec{\mathbf{E}}_1^*e^{i\omega t})\cdot\frac{1}{2}(\vec{\mathbf{E}}_2e^{-i\omega t}+\vec{\mathbf{E}}_2^*e^{i\omega t})$,

where $\mathrm{Re}\,(z)=\frac{1}{2}(z+z^*)$.

$$\vec{\mathbf{E}}_1\cdot\vec{\mathbf{E}}_2=\tfrac{1}{4}[\vec{\mathbf{E}}_1\cdot\vec{\mathbf{E}}_2e^{-2i\omega t}+\vec{\mathbf{E}}_1^*\cdot\vec{\mathbf{E}}_2^*e^{2i\omega t}+\vec{\mathbf{E}}_1\cdot\vec{\mathbf{E}}_2^*+\vec{\mathbf{E}}_1^*\cdot\vec{\mathbf{E}}_2]$$

The last two terms are time independent, while

$$\langle\vec{\mathbf{E}}_1\cdot\vec{\mathbf{E}}_2e^{-2i\omega t}\rangle\to0\quad\text{and}\quad\langle\vec{\mathbf{E}}_1^*\cdot\vec{\mathbf{E}}_2^*e^{2i\omega t}\rangle\to0$$

because of the $1/T\omega$ coefficient. Thus

$$I_{12}=2\langle\vec{\mathbf{E}}_1\cdot\vec{\mathbf{E}}_2\rangle=\tfrac{1}{2}(\vec{\mathbf{E}}_1\cdot\vec{\mathbf{E}}_2^*+\vec{\mathbf{E}}_1^*\cdot\vec{\mathbf{E}}_2)$$

9.2 The largest value of (r_1-r_2) is equal to a. Thus if $\varepsilon_1=\varepsilon_2$, $\delta=k(r_1-r_2)$ varies from 0 to ka. If $a>>\lambda$, $\cos\delta$ and therefore I_{12} will have a great many maxima and minima and therefore average to zero over a large region of space. In contrast, if $a<<\lambda$, δ varies only slightly from 0 to $ka<<2\pi$. Hence I_{12} does not average to zero. and from Eq. (9.17), I deviates little from $4I_0$. The two sources effectively behave as a single source of double the original strength.

9.4 A bulb at S would produce fringes. We can imagine it as made up of a very large number of incoherent point sources. Each of these would generate an independent pattern, all of which would then overlap. Bulbs at S_1 and S_2 would be incoherent and could not generate detectable fringes.

9.7

(a) $(r_1-r_2)=\pm\frac{1}{2}\lambda$, hence $a\sin\theta_1=\pm\frac{1}{2}\lambda$ and $\theta_1\approx\pm\frac{1}{2}\lambda/a=\pm\frac{1}{2}(632.8\times10^{-9}\,\mathrm{m})/(0.200\times10^{-3}\,\mathrm{m})=\pm1.58\times10^{-3}$ rad, or since $y_1=s\theta_1=(1.00\,\mathrm{m})(\pm1.58\times10^{-3}\,\mathrm{rad})=\pm1.58$ mm.

(b) $y_5=s5\lambda/a=(1.00\,\mathrm{m})5(632.8\times10^{-9})/(0.200\times10^{-3}\,\mathrm{m})=1.582\times10^{-2}$ m.

(c) Since the fringes vary as cosine-squared and the answer to (a) is half a fringe width, the answer to (b) is 10 times larger.

9.15 $r_2^2=a^2+r_1^2-2ar_1\cos(90-\theta)$. The contribution to $\cos\delta/2$ from the third term in the Maclaurin expansion will be negligible if

$$\frac{k}{2}\left(\frac{a^2}{2r_1}\cos^2\theta\right)<<\pi/2$$

therefore $r_1>>a^2/\lambda$.

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9.16 $E = \frac{1}{2}mv^2$; $\quad v = 0.42 \times 10^6$ m/s

$\lambda = h/mv = 1.73 \times 10^{-9}$; $\quad \Delta y = s\lambda/a = 3.46$ mm

9.22 $\Delta y = s\lambda_0/2d\alpha(n - n')$

9.23 $\Delta y = (s/a)\lambda$, $\quad a = 10^{-2}$ cm, $\quad a/2 = 5 \times 10^{-3}$ cm

9.24 $\delta = k(r_1 - r_2) + \pi$ (Lloyd's mirror)

$\delta = k\{a/2 \sin\alpha - [\sin(90 - 2\alpha)]a/2 \sin\alpha\} + \pi$

$\delta = ka(1 - \cos 2\alpha)/2 \sin\alpha + \pi$

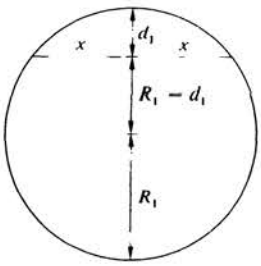
maximum occurs for

$\delta = 2\pi$ when $\sin\alpha\,(\lambda/a) = (1 - \cos 2\alpha) = 2\sin^2\alpha$

First maximum $\alpha = \sin^{-1}(\lambda/2a)$.

9.26 Here $1.00 < 1.34 > 1.00$, hence from Eq. (9.36) with $m = 0$, $d = (0 + \frac{1}{2})\,(633\text{ nm})/2(1.34) = 118$ nm.

9.29 Eq. (9.37) $m = 2n_f d/\lambda_0 = 10\,000$. A minimum, therefore central dark region.



9.30 The fringes are generally a series of fine jagged bands, which are fixed with respect to the glass.

9.31 $x^2 = d_1[(R_1 - d_1) + R_1] = 2R_1d_1 - d_1^2$

Similarly $x^2 = 2R_2d_2 - d_2^2$

$$d = d_1 - d_2 = \frac{x^2}{2}\left[\frac{1}{R_1} - \frac{1}{R_2}\right], \qquad d = m\frac{\lambda_f}{2}$$

As $R_2 \to \infty$, x_m approaches Eq. (9.43).

9.33 $\Delta x = \lambda_f/2\alpha$, $\quad \alpha = \lambda_0/2n_f\Delta x$

$\alpha = 5 \times 10^{-5}$ rad $= 10.2$ seconds

9.35 A motion of $\lambda/2$ causes a single fringe pair to shift past, hence $92\,\lambda/2 = 2.53 \times 10^{-5}$ m and $\lambda = 550$ nm.

9.39 $E_t^2 = E_tE_t^* = E_0^2(tt')^2/(1 - r^2e^{-i\delta})(1 - r^2e^{+i\delta})$

$I_t = I_i(tt')^2/(1 - r^2e^{-i\delta} - r^2e^{i\delta} + r^4)$

9.40 (a) $R = 0.80 \therefore F = 4R/(1 - R)^2 = 80$

(b) $\gamma = 4\sin^{-1} 1/\sqrt{F} = 0.448$

(c) $\mathcal{F} = 2\pi/0.448$

(d) $C = 1 + F$

9.41 $$\frac{2}{1 + F(\Delta\delta/4)^2} = 0.81\left[1 + \frac{1}{1 + F(\Delta\delta/2)^2}\right]$$

$F^2(\Delta\delta)^4 - 15.5F(\Delta\delta)^2 - 30 = 0$

9.42 $I = I_{\max}\cos^2\delta/2$

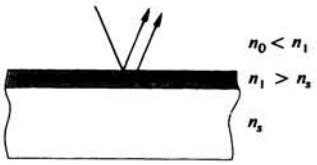
$I = I_{\max}/2$ when $\delta = \pi/2 \quad \therefore \gamma = \pi$

Separation between maxima is 2π

$$\mathcal{F} = 2\pi/\gamma = 2$$

9.44 At near normal incidence ($\theta_i \approx 0$) Fig. 4.23 *e* indicates that the relative phase shift between an internally and externally reflected beam is π rad. That means a total relative phase difference of

$$\frac{2\pi}{\lambda_f}[2(\lambda_f/4)] + \pi$$



or 2π. The waves are in phase and interfere constructively.

9.45 $n_0 = 1 \quad n_s = n_g \quad n_1 = \sqrt{n_g}$

$\sqrt{1.54} = 1.24$

$$d = \frac{1}{4}\lambda_f = \frac{1}{4}\frac{\lambda_0}{n_1} = \frac{1}{4}\frac{540}{1.24}\text{ nm}$$

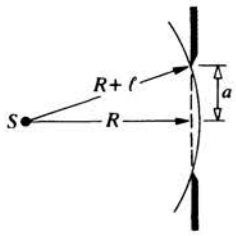
No relative phase shift between two waves.

9.46 The refracted wave will traverse the film twice, and there will be no relative phase shift on reflection. Hence

$$d = \lambda_0/4n_f = (550\text{ nm})/4(1.38) = 99.6\text{ nm}$$

Chapter 10

10.1 $(R + \ell)^2 = R^2 + a^2$; therefore $R = (a^2 - \ell^2)/2\ell \approx a^2/2\ell$, $\ell R = a^2/2$, so for $\lambda >> \ell$, $\lambda R >> a^2/2 \therefore R = (1 \times 10^{-3})^2 10/2\lambda = 10$ m.



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10.2 $E_0/2 = R \sin(\delta/2)$

$E = 2R \sin(N\delta/2)$ chord length

$E = [E_0 \sin(N\delta/2)]/\sin(\delta/2)$

$I = E^2$

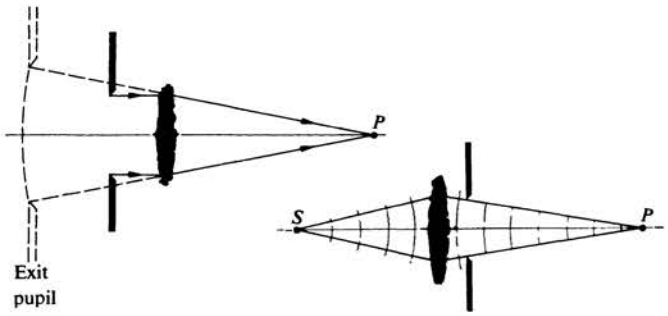
10.4 $d \sin\theta_m = m\lambda$, $\theta = N\delta/2 = \pi$

$7 \sin\theta = (1)(0.21)$ $\delta = 2\pi/N = kd \sin\theta$

$\sin\theta = 0.03$ $\sin\theta = 0.0009$

$\theta = 1.7°$ $\theta = 3$ min.

10.5 Converging spherical wave in image space is diffracted by the exit pupil.



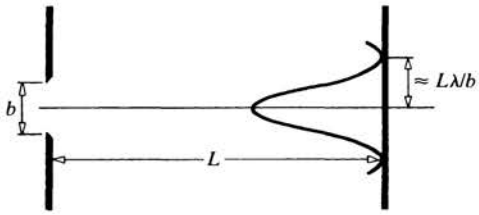
10.6 $\beta = \pm\pi$

$\sin\theta = \pm\lambda/b$

$\theta \approx \pm\lambda/b$

$L\theta \approx \pm L\lambda/b$

$L\theta \approx \pm f_2\lambda/b.$



10.9 $\lambda = (20\text{ cm}) \sin 36.87° = 12$ cm

10.10 $\alpha = \dfrac{ka}{2}\sin\theta$, $\beta = \dfrac{kb}{2}\sin\theta$

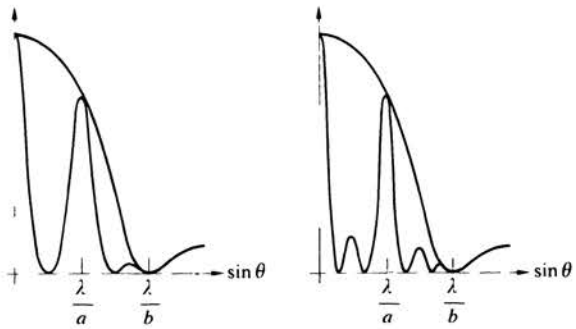
$a = mb$, $\alpha = m\beta$, $\alpha = m2\pi$

N = number of fringes $= a/\pi = m2\pi/\pi = 2m$

10.12 $\alpha = 3\pi/2N = \pi/2$ [10.34]

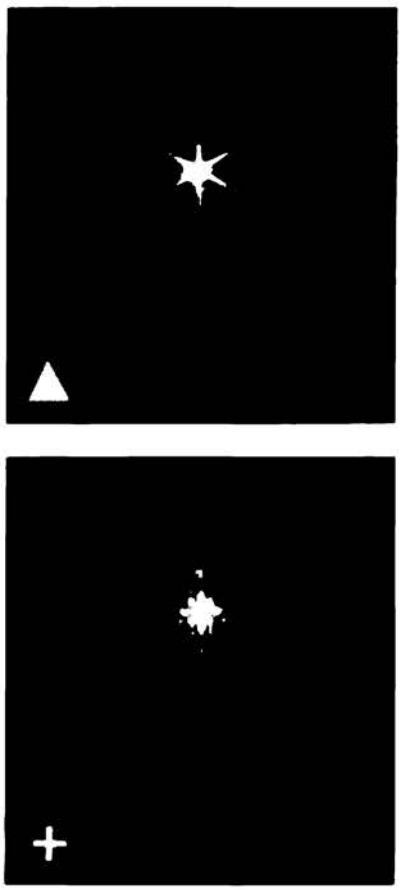
$$I(\theta) = \frac{I(0)}{N^2}\left(\frac{\sin\beta}{\beta}\right)^2 \quad \text{from Eq. (10.35)}$$

and $I/I(0) \approx \frac{1}{9}$.



10.15 If the aperture is symmetrical about a line, the pattern will be symmetrical about a line parallel to it. Moreover, the pattern will be symmetrical about yet another line perpendicular to the aperture's symmetry axis. This follows from the fact that Fraunhofer patterns have a center of symmetry.

10.16



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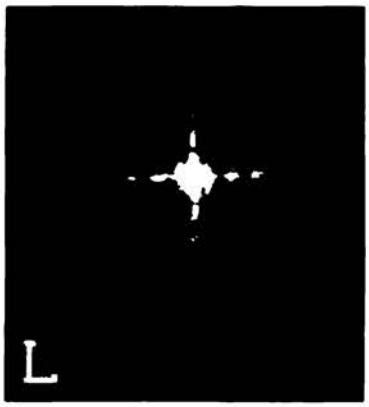
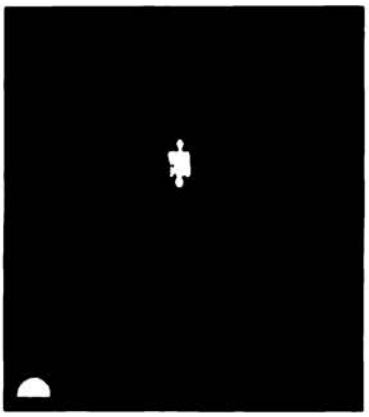
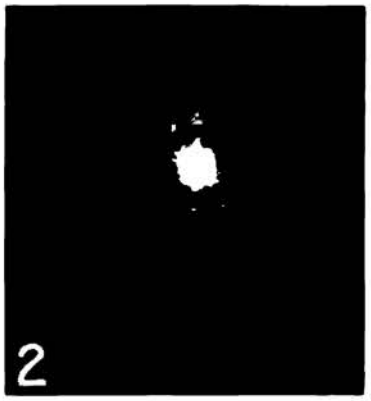
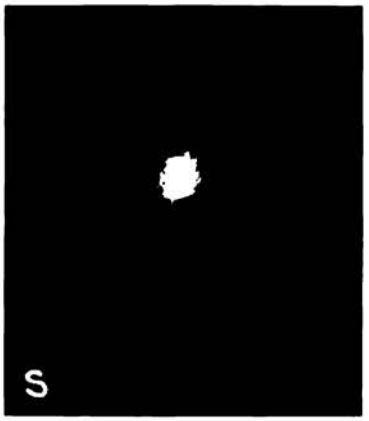
10.17 Three parallel short slits.
10.18 Two parallel short slits.
10.19 An equilateral triangular hole.
10.20 A cross-shaped hole.
10.21 The E-field of a rectangular hole.
10.23 From Eq. (10.58), $q_1 \approx 1.22(f/\mathrm{D})\lambda \approx \lambda$.
10.24









10.27 1 part in 1000. 3 yd $\approx$ 100 inches. (see Figure on p.679.)

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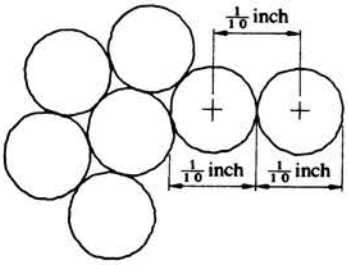


10.32 From Eq. (10.32), where $a = 1/(1000 \text{ lines per cm}) = 0.001$ cm per line (center to center), $\sin\theta_m = 1(650 \times 10^{-9}\text{ m})/(0.001 \times 10^{-2}\text{ m}) = 6.5 \times 10^{-2}$ and $\theta_1 = 3.73°$.

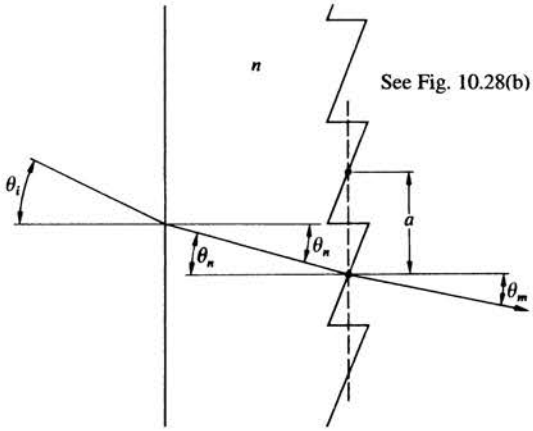
10.35 The largest value of m in Eq. (10.32) occurs when the sine function is equal to one, making the left side of the equation as large as possible, then $m = a/\lambda = (1/10 \times 10^5)/(3.0 \times 10^8\text{ m/s} \div 4.0 \times 10^{14}\text{ Hz}) = 1.3$, and only the first-order spectrum is visible.

10.37 $\sin\theta_i = n\sin\theta_n$

Optical path length difference $= m\lambda$

$a\sin\theta_m - na\sin\theta_n = m\lambda$

$a(\sin\theta_m - \sin\theta_i) = m\lambda$



10.38 $\mathcal{R} = mN = 10^6, N = 78 \times 10^3$

$\therefore m = 10^6/78 \times 10^3$

$\Delta\lambda_{\text{fsr}} = \lambda/m = 500\text{ nm}/(10^6/78 \times 10^3) = 39\text{ nm}$

$$\mathcal{R} = \mathcal{F}m = \mathcal{F}\frac{2n_f d}{\lambda} = 10^6 \qquad [9.76]$$

$$\Delta\lambda_{\text{fsr}} = \lambda^2/2n_f d = 0.0125\text{ nm} \qquad [9.78]$$

10.39 $\mathcal{R} = \lambda/\Delta\lambda = 5892.9/5.9 = 999$

$$N = \mathcal{R}/m = 333$$

10.41 $y = L\lambda/d$

$d = 12 \times 10^{-6}/12 \times 10^{-2} = 10^{-4}\text{ m}$

10.43 $A = 2\pi\rho^2\int_0^{\varphi}\sin\varphi\, d\varphi = 2\pi\rho^2(1 - \cos\varphi)$

$$\cos\varphi = [\rho^2 + (\rho + r_0)^2 - r_l^2]/2\rho(\rho + r_0)$$

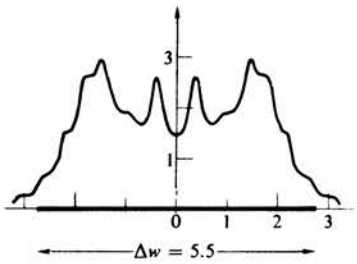
$$r_l = r_0 + l\lambda/2$$

Area of first l zones

$$A = 2\pi\rho^2 - \pi\rho(2\rho^2 + 2\rho r_0 - l\lambda r_0 - l^2\lambda^2/4)/(\rho + r_0)$$

$$A_l = A - A_{l-1} = \frac{\lambda\pi\rho}{\rho + r_0}\left[r_0 + \frac{(2l-1)\lambda}{4}\right]$$

10.45



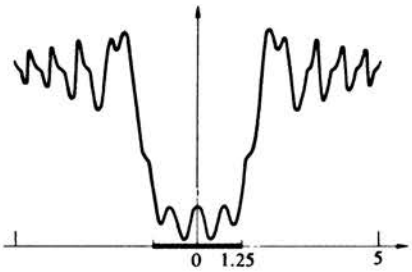
10.46 $I = \frac{I_0}{2}\{[\frac{1}{2} - \mathscr{C}(v_1)]^2 + [\frac{1}{2} - \mathscr{S}(v_1)]^2\}$

$$I = \frac{I_0}{2}\left(\frac{1}{\pi v_1}\right)^2\left[\sin^2\left(\frac{\pi v_1^2}{2}\right) + \cos^2\left(\frac{\pi v_1^2}{2}\right)\right]$$

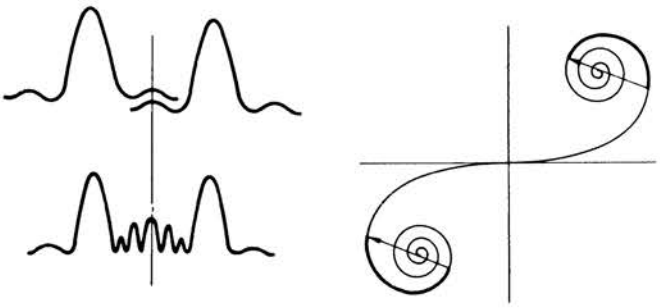
$$I = \frac{I_0}{2}\left(\frac{1}{\pi v_1}\right)^2$$

10.47 Fringes in both the clear and shadow region [(see M. P. Givens and W. L. Goffe, *Am. J. Phys.* **34**, 248 (1966)].

10.48 $u = y[2/\lambda r_0]^{1/2}$; $\Delta u = \Delta y \times 10^3 = 2.5$



10.49



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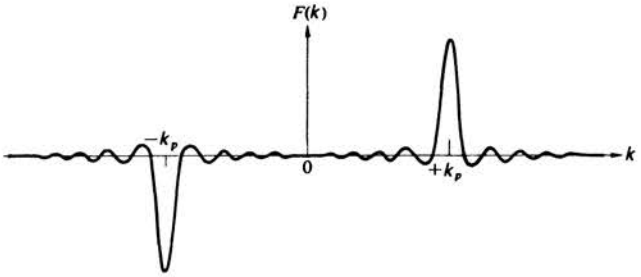
Chapter 11

11.1 $E_0 \sin k_p x = E_0(e^{ik_p x} - e^{-ik_p x})/2i$

$$F(k) = \frac{E_0}{2i}\left[\int_{-L}^{+L} e^{i(k+k_p)x}\,dx - \int_{-L}^{+L} e^{i(k-k_p)x}\,dx\right]$$

$$F(k) = -\frac{iE_0 \sin(k+k_p)L}{(k+k_p)} + \frac{iE_0 \sin(k-k_p)L}{(k-k_p)}$$

$$F(k) = iE_0L[\operatorname{sinc}(k-k_p)L - \operatorname{sinc}(k+k_p)L]$$

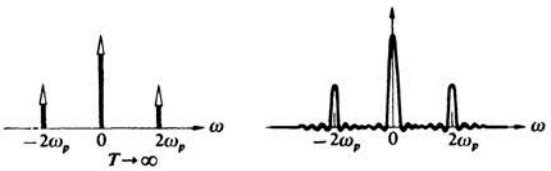


11.3 $\cos^2 \omega_p t = \frac{1}{2} + \frac{1}{2}\cos 2\omega_p t = \frac{1}{2} + \dfrac{e^{2i\omega_p t} + e^{-2i\omega_p t}}{4}$

$$F(\omega) = \tfrac{1}{2}\int_{-T}^{+T} e^{i\omega t}\,dt + \tfrac{1}{4}\int e^{i(\omega+2\omega_p)t}\,dt + \tfrac{1}{4}\int e^{i(\omega-2\omega_p)t}\,dt$$

$$F(\omega) = \frac{1}{\omega}\sin \omega T + \frac{1}{2(\omega+2\omega_p)}\sin(\omega+2\omega_p)T + \frac{1}{2(\omega-2\omega_p)}\sin(\omega-2\omega_p)T$$

$$F(\omega) = T\operatorname{sinc}\omega T + \frac{T}{2}\operatorname{sinc}(\omega+2\omega_p)T + \frac{T}{2}\operatorname{sinc}(\omega-2\omega_p)T$$



11.6 $\mathcal{F}\{af(x) + bh(x)\} = aF(k) + bH(k)$

11.8 $F(k) = L\operatorname{sinc}^2 kL/2$ at $k = 0$, $F(0) = L$, and $F(\pm 2\pi/L) = 0$.

11.15 $\displaystyle\int_{x=-\infty}^{x=+\infty} f(x)h(X-x)\,dx$

$$= -\int_{x'=+\infty}^{x'=-\infty} f(X-x')h(x')\,dx' = \int_{-\infty}^{+\infty} h(x')f(X-x')\,dx'$$

where $x' = X - x$, $dx = -dx'$.

$$f \circledast h = h \circledast f$$

or

$$\mathcal{F}\{f \circledast h\} = \mathcal{F}\{f\}\cdot\mathcal{F}\{h\} = \mathcal{F}\{h\}\cdot\mathcal{F}\{f\} = \mathcal{F}\{h \circledast f\}.$$

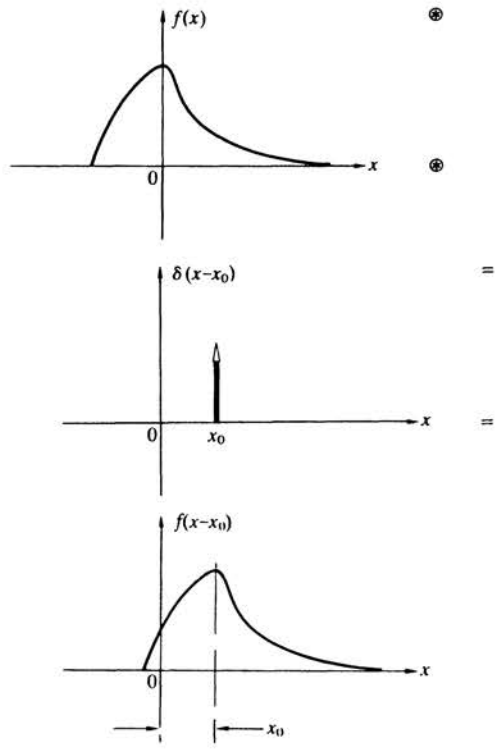
11.17 A point on the edge of $f(x, y)$, for example, at $(x = d, y = 0)$, is spread out into a square 2ℓ on a side centered on $X = d$. Thus it extends no farther than $X = d + \ell$, and so the convolution must be zero at $X = d + \ell$ and beyond.

11.19 $f(x - x_0) \circledast h(x) = \displaystyle\int_{-\infty}^{+\infty} f(x - x_0)h(X - x)dx,$

and setting $x - x_0 = \alpha$, this becomes

$$\int_{-\infty}^{+\infty} f(\alpha)h(X - \alpha - x_0)\,d\alpha = g(X - x_0)$$

11.21



11.24 We see that $f(x)$ is the convolution of a rect-function with two δ-functions, and from the convolution theorem,

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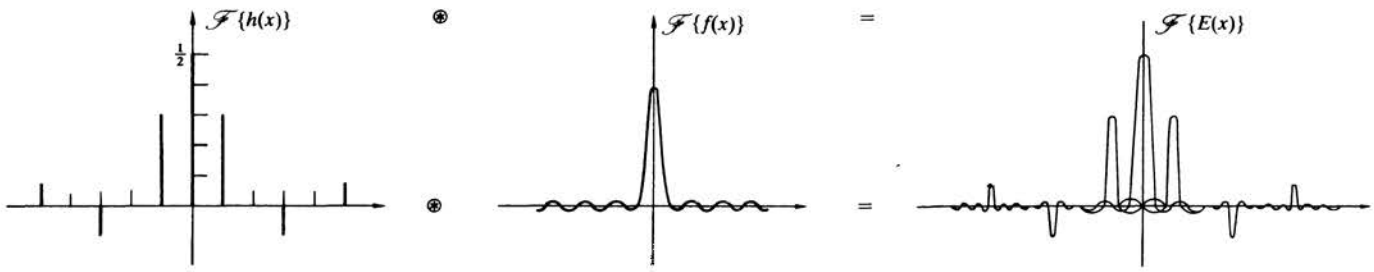
$$F(k) = \mathscr{F}\{\text{rect}(x) \circledast [\delta(x-a) + \delta(x+a)]\}$$
$$= \mathscr{F}\{\text{rect}(x)\} \cdot \mathscr{F}\{[\delta(x-a) + \delta(x+a)]\}$$
$$= a \operatorname{sinc} \tfrac{1}{2}ka \cdot (e^{ika} + e^{-ika})$$
$$= a \operatorname{sinc} (\tfrac{1}{2}ka) \cdot 2 \cos ka$$

11.25 $f(x) \circledast h(x)$

$$= [\delta(x+3) + \delta(x-2) + \delta(x-5)] \circledast h(x)$$
$$= h(x+3) + h(x-2) + h(x-5)$$

11.28



11.29 $\mathscr{A}(y, z) = \mathscr{A}(-y, -z)$

$$E(Y, Z, t) \propto \iint \mathscr{A}(y, z) e^{i(k_Y y + k_Z z)}\, dy\, dz$$

Change Y to $-Y$, Z to $-Z$, y to $-y$, z to $-z$, then k_Y goes to $-\mathsf{k}_Y$ and k_Z to $-\mathsf{k}_Z$.

$$E(-Y, -Z) \propto \iint \mathscr{A}(-y, -z) e^{i(k_Y y + k_Z z)} dy\, dz$$
$$\therefore E(-Y, -Z) = E(Y, Z)$$

11.30 From Eq. (11.63),

$$E(Y, Z) = \iint \mathscr{A}(y, z) e^{ik(Yy + Zz)/R}\, dy\, dz$$
$$E'(Y, Z) = \iint \mathscr{A}(\alpha y, \beta z) e^{ik(Yy + Zz)/R}\, dy\, dz$$

now let $y' = \alpha y$ and $z' = \beta z$:

$$E'(Y, Z) = \frac{1}{\alpha\beta} \iint \mathscr{A}(y', z') e^{ik[(Y/\alpha)y' + (Z/\beta)z']}\, dy'\, dz'$$

or
$$E'(Y, Z) = \frac{1}{\alpha\beta} E(Y/\alpha, Z/\beta)$$

11.31

$$C_{ff} = \lim_{T\to\infty} \frac{1}{2T} \int_{-T}^{+T} A \sin(\omega t + \varepsilon) A \sin(\omega t - \omega\tau + \varepsilon)\, dt$$
$$= \lim_{T\to\infty} \frac{A^2}{2T} \int [\tfrac{1}{2}\cos(\omega\tau) - \tfrac{1}{2}\cos(2\omega t - \omega\tau + 2\varepsilon)]\, dt$$

since $\cos\alpha - \cos\beta = -2 \sin \frac{1}{2}(\alpha + \beta) \sin \frac{1}{2}(\alpha - \beta)$. Thus

$$C_{ff} = \frac{A^2}{2} \cos(\omega\tau)$$

11.32 $E(k_Z) = \displaystyle\int_{-b/2}^{+b/2} \mathscr{A}_0 \cos(\pi z/b) e^{ik_Z z}\, dz$

$$= \mathscr{A}_0 \int \cos\frac{\pi z}{b} \cos k_Z z\, dz + i\mathscr{A}_0 \int \cos\frac{\pi z}{b} \sin k_Z z\, dz$$
$$E(k_Z) = \mathscr{A}_0 \cos\frac{bk_Z}{2} \left[\frac{1}{\left(\frac{\pi}{b} - k_Z\right)} + \frac{1}{\left(\frac{\pi}{b} + k_Z\right)} \right]$$

Chapter 12

12.1 At low pressures, the intensity emitted from the lamp is low, the bandwidth is narrow, and the coherence length is large. The fringes will initially display a high contrast, although they'll be fairly faint. As the pressure builds, the coherence length will decrease, the contrast will drop off, and the fringes might even vanish entirely.

12.4 Each sine function in the signal produces a cosinusoidal autocorrelation function with its own wavelength and amplitude. All of these are in phase at the zero delay point corresponding to $\tau = 0$. Beyond that origin, the cosines soon fall out of phase, producing a jumble where destructive interference is more likely. (The same sort of thing happens when, say, a square pulse is synthesized out of sinusoids—everywhere beyond the pulse all the contributions cancel.) As the number of components increases and the signal becomes more complex—resembling random noise—the autocorrelation narrows, ultimately becoming a δ-spike at $\tau = 0$.

12.6 The irradiance at Σ_0 arising from a point source is

$$4I_0 \cos^2(\delta/2) = 2I_0(1 + \cos\delta)$$

For a differential source element of width dy at point S', y from axis, the OPD to P at Y via the two slits is

$$\Lambda = (\overline{S'S_1} + \overline{S_1P}) - (\overline{S'S_2} + \overline{S_2P})$$
$$= (\overline{S'S_1} - \overline{S'S_2}) + (\overline{S_1P} - \overline{S_2P})$$
$$= ay/l + aY/s \quad \text{from Section 9.3.}$$

The contribution to the irradiance from dy is then

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$$dI \propto (1 + \cos k\Lambda)\, dy$$

$$I \propto \int_{-b/2}^{+b/2} (1 + \cos k\Lambda)\, dy$$

$$I \propto b + \frac{d}{ka}\left[\sin\left(\frac{aY}{s} + \frac{ab}{2l}\right) - \sin\left(\frac{aY}{s} - \frac{ab}{2l}\right)\right]$$

$$\begin{aligned} I \propto b + \frac{d}{ka}\,&[\sin(kaY/s)\cos(kab/2l) \\ &+ \cos(kaY/s)\sin(kab/2l) \\ &- \sin(kaY/s)\cos(kab/2l) \\ &+ \cos(kaY/s)\sin(kab/2l)] \end{aligned}$$

$$I \propto b + \frac{l2}{ka}\sin(kab/2l)\cos(kaY/s)$$

12.7

$$\mathscr{V} = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}}$$

$$I_{\max} = I_1 + I_2 + 2\sqrt{I_1 I_2}|\tilde{\gamma}_{12}|$$

$$I_{\min} = I_1 + I_2 - 2\sqrt{I_1 I_2}|\tilde{\gamma}_{12}|$$

$$\mathscr{V} = \frac{4\sqrt{I_1 I_2}|\tilde{\gamma}_{12}|}{2(I_1 + I_2)}$$

12.8 When

$$S''S_1O' - S'S_1O' - \lambda/2, 3\lambda/2, 5\lambda/2, \ldots$$

the irradiance due to S' is given by

$$I' = 4I_0\cos^2(\delta'/2) = 2I_0(1 + \cos\delta')$$

while the irradiance due to S'' is

$$\begin{aligned} I'' = 4I_0\cos^2(\delta''/2) &= 4I_0\cos^2(\delta' + \pi)/2 \\ &= 2I_0(1 - \cos\delta') \end{aligned}$$

Hence $I' + I'' = 4I_0$.

12.10 $\theta = \frac{1}{2}° = 0.008\,7$ rad

$h = 0.32\bar{\lambda}_0/\theta$ using $\bar{\lambda}_0 = 550$ nm

$h = 0.32\,(550\text{ nm})/0.008\,7$

$h = 2 \times 10^{-2}$ mm

12.11 $I_1(t) = \Delta I_1(t) + \langle I_1\rangle$
hence

$$\langle I_1(t+\tau)I_2(t)\rangle = \langle[\langle I_1\rangle + \Delta I_1(t+\tau)][\langle I_2\rangle + \Delta I_2(t)]\rangle$$

since $\langle I_1\rangle$ is independent of time.

$$\langle I_1(t+\tau)I_2(t)\rangle = \langle I_1\rangle\langle I_2\rangle + \langle\Delta I_1(t+\tau)\,\Delta I_2(t)\rangle$$

if we recall that $\langle\Delta I_1(t)\rangle + 0$. Eq. (12.34) follows by comparison with Eq. (12.32).

12.13 From Eq. (12.22), $\mathscr{V} = 2\sqrt{(10I)I}/(10I + I) = 2\sqrt{10}/11 = 0.57$.

12.15 Using the van Cittert-Zernike theorem, we can find $\tilde{\gamma}_{12}(0)$ from the diffraction pattern over the apertures, and that will yield the visibility on the observation plane: $\mathscr{V} = |\tilde{\gamma}_{12}(0)| = |\text{sinc}\,\beta|$. From Table 1, $\sin u/u = 0.85$ when $u = 0.97$, hence $\pi by/l\lambda = 0.97$, and if $y = \overline{P_1P_2} = 0.50$ mm, then $b = 0.97(l\lambda/\pi y) = 0.97(1.5\text{ m})(500 \times 10^{-9}\text{ m})/\pi(0.50 \times 10^{-3}\text{ m}) = 0.46$ mm.

12.18 From the van Cittert-Zernike theorem, the degree of coherence can be obtained from the Fourier transform of the source function, which itself is a series of δ-functions corresponding to a diffraction grating with spacing a, where $a\sin\theta_m = m\lambda$. The coherence function is therefore also a series of δ-functions. Hence the $\overline{P_1P_2}$, the slit separation d, must correspond to the location of the first-order diffraction fringe of the source if $\mathscr{V}$ is to be maximum. $a\theta_1 \approx \lambda$, and so $d \approx l\theta_1 \approx \lambda l/a = (500 \times 10^{-9}\text{ m})(2.0\text{ m})/(500 \times 10^{-6}\text{ m}) = 2.0$ mm.

Chapter 13

13.2 $P/A = \epsilon\sigma(T^4 - T_e^4) = (0.97)(5.670\,3 \times 10^{-8}\text{ W/m}^2\cdot\text{K}^4) \times (306^4 - 293^4) = I = 76.9\text{ W/m}^2$. $P = 108$ W.

13.3 $I_e = \sigma T^4$

$$(22.8\text{ W cm}^2)(10^4\text{ cm}^2/\text{m}^2) = (5.7 \times 10^{-8}\text{ W m}^{-2}\text{ K}^{-4})T^4$$

$$T = \left[\frac{22.8 \times 10^4}{5.7 \times 10^{-8}}\right]^{1/4} = 1.414 \times 10^3 = 1414\text{ K}$$

13.4 $T_2^4/T_1^4 = P_2/P_1 = 16 \times 10^{12}/16 \times 10^8 = 1.0 \times 10^4$

13.12 $\lambda(\min) = 300$ nm

$$\begin{aligned} h\nu &= hc/\lambda \\ &= \frac{(6.63 \times 10^{-34}\text{ J}\cdot\text{s})\,(3 \times 10^8\text{ m/s})}{300 \times 10^{-9}\text{ m}} \end{aligned}$$

$$\mathscr{E} = 6.63 \times 10^{-19}\text{ J} = 4.14\text{ eV}$$

13.14 $Nh\nu = (1.4 \times 10^3\text{ W/m}^2)\,(1\text{ m}^2)\,(1\text{ s})$

$$N = \frac{1.4 \times 10^3(700 \times 10^{-9})}{(6.63 \times 10^{-34})(3 \times 10^8)} = \frac{980 \times 10^{20}}{19.89}$$

$$N = 49.4 \times 10^{20}$$

13.15 Find the number of atoms present. $pV = nRT$; $n = 4.47 \times 10^{-7}$ mol; so there are 2.69×10^{17} atoms and 2.67×10^{15} get excited; the emission rate is $2.67 \times 10^{15}/\tau = 1.92 \times 10^{23}$ photons per second.

13.18 $h\nu/k_BT = 0.774$ and $\dfrac{1}{e^{0.774} - 1} = 0.86$; at the elevated temperature the ratio is substantial, and the two modalities are com-

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parable.

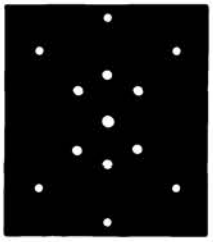
13.23 The transition rate must equal $P/h\nu = 3 \times 10^{15}\ \mathrm{s}^{-1}$.

13.27 $I = \frac{1}{2} v \epsilon E_0^2 = \frac{n}{2}\left(\frac{\epsilon_0}{\mu_0}\right)^{1/2} E_0^2$, where $\mu \approx \mu_0$

$$E_0^2 = 2(\mu_0/\epsilon_0)^{1/2} I/n \qquad (\mu_0/\epsilon_0)^{1/2} = 376.730\ \Omega$$

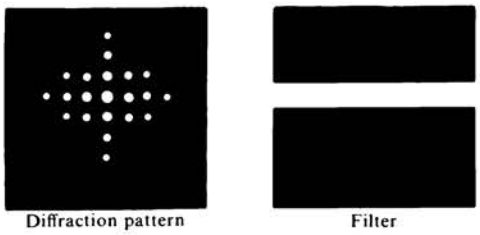
$$E_0 = 27.4\ (I/n)^{1/2}$$

13.29



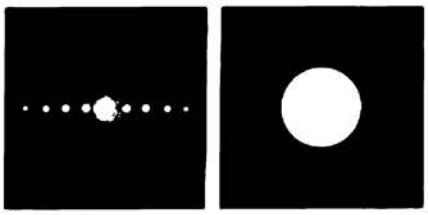
Diffraction pattern

13.30



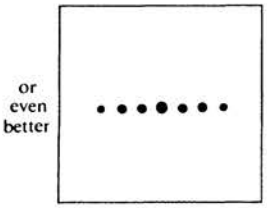
Diffraction pattern Filter

13.31



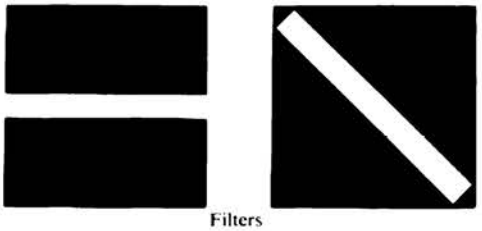
Diffraction pattern Filter

13.33



Filter

13.34 From the geometry, $f_t\theta = f_i\Phi$: $k_O = k \sin\theta$ and $k_I = k \sin\Phi$.



Filters

hence $\sin\theta \approx \theta \approx k_O\lambda/2\pi$ and $\sin\Phi \approx \Phi \approx k_I\lambda/2\pi$, therefore $\theta/\Phi = k_O/k_I$ and $k_I = k_O(\Phi/\theta) = k_O(f_t/f_i)$. When $f_i > f_t$ the image will be larger than the object, the spatial periods in the image will also be larger, and the spatial frequencies in the image will be smaller than in the object.

13.35 $a = (1/50)$ cm: $a \sin\theta = m\lambda$, $\sin\theta \approx \theta$, hence $\theta = (5000\ \mathrm{m})\,\lambda$, and the distance between orders on the transform plane is $f\theta = 5000\,\lambda f = 2.7$ mm.

13.37 Each point on the diffraction pattern corresponds to a single spatial frequency, and if we consider the diffracted wave to be made up of plane waves, it also corresponds to a single-plane wave direction. Such waves, by themselves, carry no information about the periodicity of the object and produce a more or less uniform image. The periodicity of the source arises in the image when the component plane waves interfere.

13.39 The relative field amplitudes are 1.00, 0.60, and 0.60; hence $E \propto 1 + 0.60\cos(+ky') + 0.60\cos(-ky') = 1 + 1.2\cos ky'$. This is a cosine oscillating about a line equal to 1.0. It varies from +2.2 to −0.2. The square of this will correspond to the irradiance, and it will be a series of tall peaks with a relative height of $(2.2)^2$, between each pair of which there will be a short peak proportional to $(0.2)^2$; notice the similarity with Fig. 11.32.

13.40 $a \sin\theta = \lambda$, here $f\theta = 50\lambda f = 0.20$ cm; hence $\lambda = 0.20/50(100) = 400$ nm. The magnification is 1.0 when the focal lengths are equal; hence the spacing is again 50 wires/cm.

13.44 The inherent motion of the medium would cause the speckle pattern to vanish.

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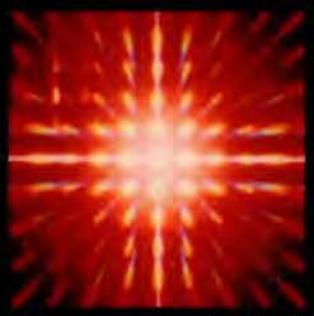

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