Michelson interferometer: The Michelson interferometer uses a monochromatic light source and can be used for high-precision measurements of wavelengths. Its original purpose was to detect motion of the earth relative to a hypothetical ether, the supposed medium for electromagnetic waves. The ether has never been detected, and the concept has been abandoned; the speed of light is the same relative to all observers. This is part of the foundation of the special theory of relativity.

**Discussion Questions**

Q35.1 A two-slit interference experiment is set up, and the fringes are displayed on a screen. Then the whole apparatus is immersed in the nearest swimming pool. How does the fringe pattern change?

Q35.2 Could an experiment similar to Young’s two-slit experiment be performed with sound? How might this be carried out? Does it matter that sound waves are longitudinal and electromagnetic waves are transverse? Explain.

Q35.3 Monochromatic coherent light passing through two thin slits is viewed on a distant screen. Are the bright fringes equally spaced on the screen? If so, why? If not, which ones are closest to being equally spaced?

Q35.4 In a two-slit interference pattern on a distant screen, are the bright fringes midway between the dark fringes? Is this ever a good approximation?

Q35.5 Would the headlights of a distant car form a two-source interference pattern? If so, how might it be observed? If not, why not?

Q35.6 The two sources $S_1$ and $S_2$ shown in Fig. 35.3 emit waves of the same wavelength $\lambda$ and are in phase with each other. Suppose $S_1$ is a weaker source, so that the waves emitted by $S_1$ have half the amplitude of the waves emitted by $S_2$. How would this affect the positions of the antinodal lines and nodal lines? Would there be total reinforcement at points on the antinodal curves? Would there be total cancellation at points on the nodal curves? Explain your answers.

Q35.7 Could the Young two-slit interference experiment be performed with gamma rays? If not, why not? If so, discuss differences in the experimental design compared to the experiment with visible light.

Q35.8 Coherent red light illuminates two narrow slits that are 25 cm apart. Will a two-slit interference pattern be observed when the light from the slits falls on a screen? Explain.

Q35.9 Coherent light with wavelength $\lambda$ falls on two narrow slits separated by a distance $d$. If $d$ is less than some minimum value,
no dark fringes are observed. Explain. In terms of \(A\), what is this minimum value of \(d\)?

**Q35.10** A fellow student, who values memorizing equations above understanding them, combines Eqs. (35.4) and (35.13) to “prove” that \(\phi\) can only equal \(2\pi m\). How would you explain to this student that \(\phi\) can have values other than \(2\pi m\)?

**Q35.11** If the monochromatic light shown in Fig. 35.5a were replaced by white light, would a two-slit interference pattern be seen on the screen? Explain.

**Q35.12** In using the superposition principle to calculate intensities in interference patterns, could you add the intensities of the waves instead of their amplitudes? Explain.

**Q35.13** A glass windowpane with a thin film of water on it reflects less than when it is perfectly dry. Why?

**Q35.14** A very thin soap film \((n = 1.33)\), whose thickness is much less than a wavelength of visible light, looks black; it appears to reflect no light at all. Why? By contrast, an equally thin layer of soapy water \((n = 1.33)\) on glass \((n = 1.50)\) appears quite shiny. Why is there a difference?

**Q35.15** Interference can occur in thin films. Why is it important that the films be thin? Why don’t you get these effects with a relatively thick film? Where should you put the dividing line between “thin” and “thick”? Explain your reasoning.

**Q35.16** If we shine white light on an air wedge like that shown in Fig. 35.12, the colors that are weak in the light reflected from any point along the wedge are strong in the light transmitted through the wedge. Explain why this should be so.

**Q35.17** Monochromatic light is directed at normal incidence on a thin film. There is destructive interference for the reflected light, so the intensity of the reflected light is very low. What happened to the energy of the incident light?

**Q35.18** When a thin oil film spreads out on a puddle of water, the thinnest part of the film looks dark in the resulting interference pattern. What does this tell you about the relative magnitudes of the refractive indexes of oil and water?

### EXERCISES

#### Section 35.1 Interference and Coherent Sources

**35.1** Two small stereo speakers \(A\) and \(B\) that are 1.40 m apart are sending out sound of wavelength 34 cm in all directions and all in phase. A person at point \(P\) starts out equidistant from both speakers and walks so that he is always 1.50 m from speaker \(B\) (Fig. E35.1). For what values of \(x\) will the sound this person hears be (a) maximally reinforced, (b) cancelled? Limit your solution to the cases where \(x \approx 1.50\) m.

**35.2** Two speakers that are 15.0 m apart produce in-phase sound waves of frequency 250.0 Hz in a room where the speed of sound is 340.0 m/s. A woman starts out at the midpoint between the two speakers. The room’s walls and ceiling are covered with absorbers to eliminate reflections, and she listens with only one ear for best precision. (a) What does she hear: constructive or destructive interference? Why? (b) She now walks slowly toward one of the speakers. How far from the center must she walk before she first hears the sound reach a minimum intensity? (c) How far from the center must she walk before she first hears the sound maximally enhanced?

**35.3** Two identical audio speakers connected to the same amplifier produce in-phase sound waves with a single frequency that can be varied between 300 and 600 Hz. The speed of sound is 340 m/s. You find that where you are standing, you hear minimum-intensity sound. (a) Explain why you hear minimum-intensity sound. (b) If one of the speakers is moved 39.8 cm toward you, the sound you hear has maximum intensity. What is the frequency of the sound? (c) How much closer to you from the position in part (b) must the speaker be moved to the next position where you hear maximum intensity?

**35.4** Radio Interference. Two radio antennas \(A\) and \(B\) radiate in phase. Antenna \(B\) is 120 m to the right of antenna \(A\). Consider point \(Q\) along the extension of the line connecting the antennas, a horizontal distance of 40 m to the right of antenna \(B\). The frequency, and hence the wavelength, of the emitted waves can be varied. (a) What is the longest wavelength for which there will be destructive interference at point \(Q\)? (b) What is the longest wavelength for which there will be constructive interference at point \(Q\)?

**35.5** A radio transmitting station operating at a frequency of 120 MHz has two identical antennas that radiate in phase. Antenna \(B\) is 9.00 m to the right of antenna \(A\). Consider point \(P\) between the antennas and along the line connecting them, a horizontal distance \(x\) to the right of antenna \(A\). For what values of \(x\) will constructive interference occur at point \(P\)?

**35.6** Two light sources can be adjusted to emit monochromatic light of any visible wavelength. The two sources are coherent, 2.04 \(\mu\)m apart, and in line with an observer, so that one source is 2.04 \(\mu\)m farther from the observer than the other. (a) For what visible wavelengths (380 to 750 nm) will the observer see the brightest light, owing to constructive interference? (b) How would your answers to part (a) be affected if the two sources were not in line with the observer, but were still arranged so that one source is 2.04 \(\mu\)m farther away from the observer than the other? (c) For what visible wavelengths will there be destructive interference at the location of the observer?

**35.7** Two speakers, emitting identical sound waves of wavelength 2.0 m in phase with each other, and an observer are located as shown in Fig. E35.7. (a) At the observer’s location, what is the path difference for waves from the two speakers? (b) Will the sound waves interfere constructively or destructively at the observer’s location—or something in between constructive and destructive? (c) Suppose the observer now increases her distance from the closest speaker to 17.0 m, staying directly in front of the same speaker as initially. Answer the questions of parts (a) and (b) for this new situation.

**35.8** Figure 35.3 shows the wave pattern produced by two identical, coherent sources emitting waves with wavelength \(\lambda\) and separated by a distance \(d = 4\lambda\). (a) Explain why the positive y-axis above \(S_1\) constitutes an antinodal curve with \(m = +4\) and why the negative y-axis below \(S_2\) constitutes an antinodal curve with \(m = -4\). (b) Draw the wave pattern produced when the separation between the sources is reduced to \(3\lambda\). In your drawing, sketch all antinodal curves—that is, the curves on which \(r_2 - r_1 = m\lambda\). Label each curve by its value of \(m\). (c) In general, what determines the maximum (most positive) and minimum (most negative) values of the integer \(m\) that labels the antinodal lines? (d) Suppose the separation between the sources is increased...
to $7\lambda$. How many antinodal curves will there be? To what values of $n$ do they correspond? Explain your reasoning. (You should not have to make a drawing to answer these questions.)

Section 35.2 Two-Source Interference of Light

35.5 • Young’s experiment is performed with light from excited helium atoms ($\lambda = 502$ nm). Fringes are measured carefully on a screen 1.20 m away from the double slit, and the center of the 20th fringe (not counting the central bright fringe) is found to be 10.6 mm from the center of the central bright fringe. What is the separation of the two slits?

35.10 • Coherent light with wavelength 450 nm falls on a double slit. On a screen 1.80 m away, the distance between dark fringes is 4.20 mm. What is the separation of the slits?

35.11 • Two slits spaced 0.450 mm apart are placed 75.0 cm from a screen. What is the distance between the second and third dark lines of the interference pattern on the screen when the slits are illuminated with coherent light with a wavelength of 500 nm?

35.12 • If the entire apparatus of Exercise 35.11 (slits, screen, and space in between) is immersed in water, what then is the distance between the second and third dark lines?

35.13 • Two thin parallel slits that are 0.0116 mm apart are illuminated by a laser beam of wavelength 585 nm. (a) On a very large distant screen, what is the total number of bright fringes (those indicating complete constructive interference), including the central fringe and those on both sides of it? Solve this problem without calculating all the angles! (Hint: What is the largest that $\sin \theta$ can be? What does this tell you is the largest value of $n$?) (b) At what angle, relative to the original direction of the beam, will the fringe that is most distant from the central bright fringe occur?

35.14 • Coherent light with wavelength 400 nm passes through two very narrow slits that are separated by 0.200 mm, and the interference pattern is observed on a screen 4.00 m from the slits. (a) What is the width (in mm) of the central interference maximum? (b) What is the width of the first-order bright fringe?

35.15 • Two very narrow slits are spaced 1.80 $\mu$m apart and are placed 35.0 cm from a screen. What is the distance between the first and second dark lines of the interference pattern when the slits are illuminated with coherent light with $\lambda = 550$ nm? (Hint: The angle $\theta$ in Eq. (35.5) is not small.)

35.16 • Coherent light that contains two wavelengths, 660 nm (red) and 470 nm (blue), passes through two narrow slits separated by 0.300 mm, and the interference pattern is observed on a screen 5.00 m from the slits. What is the distance on the screen between the first-order bright fringes for the two wavelengths?

35.17 • Coherent light with wavelength 600 nm passes through two very narrow slits and the interference pattern is observed on a screen 3.00 m from the slits. The first-order bright fringe is at 4.84 mm from the center of the central bright fringe. For what wavelength of light will the first-order dark fringe be observed at this same point on the screen?

35.18 • Coherent light of frequency $6.32 \times 10^{14}$ Hz passes through two thin slits and falls on a screen 85.0 cm away. You observe that the third bright fringe occurs at $\pm 3.11$ cm on either side of the central bright fringe. (a) How far apart are the two slits? (b) At what distance from the central bright fringe will the third dark fringe occur?

Section 35.3 Intensity in Interference Patterns

35.19 • In a two-slit interference pattern, the intensity at the peak of the central maximum is $I_0$. (a) At a point in the pattern where the phase difference between the waves from the two slits is 60°, what is the intensity? (b) What is the path difference for 480-nm light from the two slits at a point where the phase angle is 60°?

35.20 • Coherent sources $A$ and $B$ emit electromagnetic waves with wavelength 2.00 cm. Point $P$ is 4.86 m from $A$ and 5.24 m from $B$. What is the phase difference at $P$ between these two waves?

35.21 • Coherent light with wavelength 500 nm passes through narrow slits separated by 0.340 mm. At a distance from the slits large compared to their separation, what is the phase difference (in radians) in the light from the two slits at an angle of 23.0° from the centerline?

35.22 • Two slits spaced 0.260 mm apart are placed 0.700 m from a screen and illuminated by coherent light with a wavelength of 660 nm. The intensity at the center of the central maximum ($\theta = 0^\circ$) is $I_0$. (a) What is the distance on the screen from the center of the central maximum to the first minimum? (b) What is the distance on the screen from the center of the central maximum to the point where the intensity has fallen to $I_0/2$?

35.23 • Points $A$ and $B$ are 56.0 m apart along an east-west line. At each of these points, a radio transmitter is emitting a 12.5-MHz signal horizontally. These transmitters are in phase with each other and emit their beams uniformly in a horizontal plane. A receiver is taken 0.500 km north of the $AB$ line and initially placed at point $C$, directly opposite the midpoint of $AB$. The receiver can be moved only along an east-west direction but, due to its limited sensitivity, it must always remain within a range so that the intensity of the signal it receives from the transmitter is no less than $\frac{1}{2}$ of its maximum value. How far from point $C$ (along an east-west line) can the receiver be moved and always be able to pick up the signal?

35.24 • Consider two antennas separated by 9.00 m that radiate in phase at 120 MHz, as described in Exercise 35.5. A receiver placed 150 m from both antennas measures an intensity $I_0$. The receiver is moved so that it is 1.8 m closer to one antenna than to the other. (a) What is the phase difference $\phi$ between the two radio waves produced by this path difference? (b) In terms of $I_0$, what is the intensity measured by the receiver at its new position?

Section 35.4 Interference in Thin Films

35.25 • What is the thinnest film of a coating with $n = 1.42$ on glass ($n = 1.52$) for which destructive interference of the red component (650 nm) of an incident white light beam in air can take place by reflection?

35.26 • Nonglare Glass. When viewing a piece of art that is behind glass, one often is affected by the light that is reflected off the front of the glass (called glare), which can make it difficult to see the art clearly. One solution is to coat the outer surface of the glass with a film to cancel part of the glare. (a) If the glass has a refractive index of 1.62 and you use TiO$_2$, which has an index of refraction of 2.62, as the coating, what is the minimum film thickness that will cancel light of wavelength 505 nm? (b) If this coating is too thin to stand up to wear, what other thickness would also work? Find only the three thinnest ones.

35.27 • Two rectangular pieces of plane glass are laid one upon the other on a table. A thin strip of paper is placed between them at one edge so that a very thin wedge of air is formed. The plates are illuminated at normal incidence by 546-nm light from a mercury-vapor lamp. Interference fringes are formed, with 15.0 fringes per centimeter. Find the angle of the wedge.

35.28 • A plate of glass 9.00 cm long is placed in contact with a second plate and is held at a small angle with it by a metal strip.
0.0800 mm thick placed under one end. The space between the plates is filled with air. The glass is illuminated from above with light having a wavelength in air of 656 nm. How many interference fringes are observed per centimeter in the reflected light?

35.29 • A uniform film of TiO₂, 1036 nm thick and having index of refraction 2.62, is spread uniformly over the surface of crown glass of refractive index 1.52. Light of wavelength 520.0 nm falls at normal incidence onto the film from air. You want to increase the thickness of this film so that the reflected light cancels. (a) What is the minimum thickness of TiO₂ that you must add so the reflected light cancels as desired? (b) After you make the adjustment in part (a), what is the path difference between the light reflected off the top of the film and the light that cancels it after traveling through the film? Express your answer in (i) nanometers and (ii) wavelengths of the light in the TiO₂ film.

35.30 • A plastic film with index of refraction 1.85 is put on the surface of a car window to increase the reflectivity and thus to keep the interior of the car cooler. The window glass has index of refraction 1.52. (a) What minimum thickness is required if light with wavelength 550 nm in air reflected from the two sides of the film is to interfere constructively? (b) It is found to be difficult to manufacture and install coatings as thin as calculated in part (a). What is the next greatest thickness for which there will also be constructive interference?

35.31 • The walls of a soap bubble have about the same index of refraction as that of plain water, n = 1.33. There is air both inside and outside the bubble. (a) What wavelength (in air) of visible light is most strongly reflected from a point on a soap bubble where its wall is 290 nm thick? To what color does this correspond? (b) Repeat part (a) for a wall thickness of 340 nm.

35.32 • Light with wavelength 648 nm in air is incident perpendicularly from air on a film 8.76 μm thick and with refractive index 1.35. Part of the light is reflected from the first surface of the film, and part enters the film and is reflected back at the second surface, where the film is again in contact with air. (a) How many waves are contained along the path of this second part of the light in its round trip through the film? (b) What is the phase difference between these two parts of the light as they leave the film?

35.33 • Compact Disc Player. A compact disc (CD) is read from the bottom by a semiconductor laser with wavelength 790 nm passing through a plastic substrate of refractive index 1.8. When the beam encounters a pit, part of the beam is reflected from the pit and part from the flat region between the pits, so these two beams interfere with each other (Fig. E35.33). What must the minimum pit depth be so that the part of the beam reflected from a pit cancels the part of the beam reflected from the flat region? (It is this cancellation that allows the player to recognize the beginning and end of a pit.)

35.34 • What is the thinnest soap film (excluding the case of zero thickness) that appears black when illuminated with light with wavelength 480 nm? The index of refraction of the film is 1.33, and there is air on both sides of the film.

Section 35.5 The Michelson Interferometer

35.35 • How far must the mirror M₂ (see Fig. 35.19) of the Michelson interferometer be moved so that 1800 fringes of He-Ne laser light (λ = 633 nm) move across a line in the field of view?

35.36 • Jan first uses a Michelson interferometer with the 606-nm light from a krypton-86 lamp. He displaces the movable mirror away from him, counting 818 fringes moving across a line in his field of view. Then Linda replaces the krypton lamp with filtered 502-nm light from a helium lamp and displaces the movable mirror toward her. She also counts 818 fringes, but they move across the line in her field of view opposite to the direction they moved for Jan. Assume that both Jan and Linda counted to 818 correctly. (a) What distance did each person move the mirror? (b) What is the resultant displacement of the mirror?

PROBLEMS

35.37 • The radius of curvature of the convex surface of a planoconvex lens is 68.4 cm. The lens is placed convex side down on a perfectly flat glass plate that is illuminated from above with red light having a wavelength of 580 nm. Find the diameter of the second bright ring in the interference pattern.

35.38 • Newton’s rings can be seen when a planoconvex lens is placed on a flat glass surface. For a particular lens with an index of refraction of n = 1.50 and a glass plate with an index of n = 1.80, the diameter of the third bright ring is 0.720 mm. If water (n = 1.33) now fills the space between the lens and the plate, what is the new diameter of this ring?

35.39 • Coating Eyeglass Lenses. Eyeglass lenses can be coated on the inner surfaces to reduce the reflection of stray light to the eye. If the lenses are medium flint glass of refractive index 1.62 and the coating is fluorite of refractive index 1.432, (a) what minimum thickness of film is needed on the lenses to cancel light of wavelength 550 nm reflected toward the eye at normal incidence? (b) Will any other wavelengths of visible light be cancelled or enhanced in the reflected light?

35.40 • Sensitive Eyes. After an eye examination, you put some eyedrops on your sensitive eyes. The cornea (the front part of the eye) has an index of refraction of 1.38, while the eyeballs have a refractive index of 1.45. After you put in the drops, your friends notice that your eyes look red, because red light of wavelength 600 nm has been reinforced in the reflected light. (a) What is the minimum thickness of the film of eyedrops on your cornea? (b) Will any other wavelengths of visible light be reinforced in the reflected light? Will any be cancelled? (c) Suppose you had contact lenses, so that the eyedrops went on them instead of on your corneas. If the refractive index of the lens material is 1.50 and the layer of eyedrops has the same thickness as in part (a), what wavelengths of visible light will be reinforced? What wavelengths will be cancelled?

35.41 • Two flat plates of glass with parallel faces are on a table, one plate on the other. Each plate is 11.0 cm long and has a refractive index of 1.55. A very thin sheet of metal foil is inserted under the end of the upper plate to raise it slightly at that end, in a manner similar to that discussed in Example 35.4. When you view the glass plates from above with reflected white light, you observe that, at 1.15 mm from the line where the sheets are in contact, the violet light of wavelength 400.0 nm is enhanced in this reflected light, but no visible light is enhanced closer to the line of contact.
(a) How far from the line of contact will green light (of wavelength 550 nm) and orange light (of wavelength 600.0 nm) first be enhanced? (b) How far from the line of contact will the violet, green, and orange light again be enhanced in the reflected light? (c) How thick is the metal foil holding the ends of the plates apart?

35.42 In a setup similar to that of Problem 35.41, the glass has an index of refraction of 1.53, the plates are each 8.00 cm long, and the metal foil is 0.015 mm thick. The space between the plates is filled with a jelly whose refractive index is not known precisely, but is known to be greater than that of the glass. When you illuminate these plates from above with light of wavelength 525 nm, you observe a series of equally spaced dark fringes in the reflected light. You measure the spacing of these fringes and find that there are 10 of them every 6.33 mm. What is the index of refraction of the jelly?

35.43 Suppose you illuminate two thin slits by monochromatic coherent light in air and find that they produce their first interference minima at $\pm 35.20^\circ$ on either side of the central bright spot. You then immerse these slits in a transparent liquid and illuminate them with the same light. Now you find that the first minima occur at $\pm 19.46^\circ$ instead. What is the index of refraction of this liquid?

35.44 CP CALC A very thin sheet of brass contains two thin parallel slits. When a laser beam shines on these slits at normal incidence and room temperature (20.0°C), the first interference dark fringes occur at $\pm 32.5^\circ$ from the original direction of the laser beam when viewed from some distance. If this sheet is now slowly heated up to 135°C, by how many degrees do these dark fringes change position? Do they move closer together or get farther apart? See Table 17.1 for pertinent information, and ignore any effects that might occur due to change in the thickness of the slits. (Hint: Since thermal expansion normally produces very small changes in length, you can use differentials to find the change in the angle.)

35.45 Two speakers, 2.50 m apart, are driven by the same audio oscillator so that each one produces a sound consisting of two distinct frequencies, 0.900 kHz and 1.20 kHz. The speed of sound in the room is 344 m/s. Find all the angles relative to the usual centerline in front of (and far from) the speakers at which both frequencies interfere constructively.

35.46 Two radio antennas radiating in phase are located at points A and B, 200 m apart (Fig. P35.46). The radio waves have a frequency of 5.80 MHz. A radio receiver is moved out from point B along a line perpendicular to the line connecting A and B (line BC shown in Fig. P35.46). At what distances from B will there be destructive interference? (Note: The distance of the receiver from the sources is not large in comparison to the separation of the sources, so Eq. (35.5) does not apply.)

35.47 One round face of a 3.25-m, solid, cylindrical plastic pipe is covered with a thin black coating that completely blocks light. The opposite face is covered with a fluorescent coating that glows when it is struck by light. Two straight, thin, parallel scratches, 0.225 mm apart, are made in the center of the black face. When laser light of wavelength 632.8 nm shines through the slits perpendicular to the black face, you find that the central bright fringe on the opposite face is 5.82 mm wide, measured between the dark fringes that border it on either side. What is the index of refraction of the plastic?

35.48 A uniform thin film of material of refractive index 1.40 coats a glass plate of refractive index 1.55. This film has the proper thickness to cancel normally incident light of wavelength 525 nm that strikes the film surface from air, but it is somewhat greater than the minimum thickness to achieve this cancellation. As time goes by, the film wears away at a steady rate of 4.20 nm per year. What is the minimum number of years before the reflected light of this wavelength is now enhanced instead of cancelled?

35.49 Two speakers A and B are 3.50 m apart, and each one is emitting a frequency of 444 Hz. However, because of signal delays in the cables, speaker A is one-fourth of a period ahead of speaker B. For points far from the speakers, find all the angles relative to the centerline (Fig. P35.49) at which the sound from these speakers cancels. Include angles on both sides of the centerline. The speed of sound is 340 m/s.

35.50 CP The electric fields received at point P from two identical, coherent wave sources are $E_1(t) = E_0 \cos(\omega t + \phi)$ and $E_2(t) = E_0 \cos(\omega t)$. (a) Use the trigonometric identities in Appendix B to show that the resultant wave is $E(t) = 2E_0 \cos(\phi/2) \cos(\omega t + \phi/2)$. (b) Show that the amplitude of this resultant wave is given by Eq. (35.7). (c) Use the result of part (a) to show that at an interference maximum, the amplitude of the resultant wave is in phase with the original waves $E_1(t)$ and $E_2(t)$. (d) Use the result of part (a) to show that near an interference minimum, the resultant wave is approximately $\frac{1}{2}$ cycle out of phase with either of the original waves. (e) Show that the instantaneous Poynting vector at point P has magnitude $S = 4\epsilon_0 E^2 \cos^2(\phi/2) \cos^2(\omega t + \phi/2)$ and that the time-averaged Poynting vector is given by Eq. (35.9).

35.51 CP A thin uniform film of refractive index 1.750 is placed on a sheet of glass of refractive index 1.50. At room temperature (20.0°C), this film is just thick enough for light with wavelength 582.4 nm reflected off the top of the film to be cancelled by light reflected from the top of the glass. After the glass is placed in an oven and slowly heated to 170°C, you find that the film cancels reflected light with wavelength 588.5 nm. What is the coefficient of linear expansion of the film? (Ignore any changes in the refractive index of the film due to the temperature change.)

35.52 GPS Transmission. The GPS (Global Positioning System) satellites are approximately 5.18 m across and transmit two low-power signals, one of which is at 1575.42 MHz (in the UHF band). In a series of laboratory tests on the satellite, you put two 1575.42-MHz UHF transmitters at opposite ends of the satellite. These broadcast in phase uniformly in all directions. You measure the intensity at points on a circle that is several hundred meters in radius and centered on the satellite. You measure angles on this circle relative to a point that lies along the centerline of the satellite (that is, the perpendicular bisector of a line that extends from one transmitter to the other). At this point on the circle, the measured intensity is 2.00 W/m². (a) At how many other angles in the range $0^\circ < \theta < 90^\circ$ is the intensity also 2.00 W/m²? (b) Find the four smallest angles in the range $0^\circ < \theta < 90^\circ$ for which the intensity is 2.00 W/m². (c) What is the intensity at a point on the circle at an angle of 4.65° from the centerline?

35.53 Consider a two-slit interference pattern, for which the intensity distribution is given by Eq. (35.14). Let $\theta_m$ be the angular
position of the \( m \)th bright fringe, where the intensity is \( I_0 \). Assume that \( \theta_m \) is small, so that \( \sin \theta_m = \theta_m \). Let \( \theta_m^+ \) and \( \theta_m^- \) be the two angles on either side of \( \theta_m \) for which \( I = \frac{1}{2} I_0 \). The quantity 
\[
\Delta \theta_m = |\theta_m^+ - \theta_m^-|
\]
is the half-width of the \( m \)th fringe. Calculate \( \Delta \theta_m \). How does \( \Delta \theta_m \) depend on \( m \)?

35.54 White light reflects at normal incidence from the top and bottom surfaces of a glass plate \((n = 1.52)\). There is air above and below the plate. Constructive interference is observed for light whose wavelength in air is 477.0 nm. What is the thickness of the plate if the next longer wavelength for which there is constructive interference is 540.6 nm?

35.55 A source \( S \) of monochromatic light and a detector \( D \) are both located in air a distance \( h \) above a horizontal plane sheet of glass and are separated by a horizontal distance \( x \). Waves reaching \( D \) directly from \( S \) interfere with waves that reflect off the glass. The distance \( x \) is small compared to \( h \) so that the reflection is at close to normal incidence. (a) Show that the condition for constructive interference is 
\[
\sqrt{x^2 + 4h^2} = n\lambda,
\]
and the condition for destructive interference is 
\[
\sqrt{x^2 + 4h^2} = n\lambda/2.
\]
(Hint: Take into account the phase change on reflection.) (b) Let \( h = 24 \) cm and \( x = 14 \) cm. What is the longest wavelength for which there will be constructive interference?

35.56 BIO Reflective Coatings and Herring. Herring and related fish have a brilliant silvery appearance that camouflages them while they are swimming in a sunlit ocean. The silveriness is due to platelets attached to the surfaces of these fish. Each platelet is made up of several alternating layers of crystalline guanine \((n = 1.8)\) and of cytoplasm \((n = 1.33)\), the same as water, with a guanine layer on the outside in contact with the surrounding water (Fig. P35.56). In one typical platelet, the guanine layers are 74 nm thick and the cytoplasm layers are 100 nm thick. (a) For light striking the platelet surface at normal incidence, for which vacuum wavelengths of visible light will all of the reflections \( R_1, R_2, R_3, R_4, \) and \( R_5 \), shown in Fig. P35.56, be approximately in phase? If white light is shone on this platelet, what color will be most strongly reflected (see Fig. 32.4)? The surface of a herring has very many platelets side by side with layers of different thickness, so that all visible wavelengths are reflected. (b) Explain why such a “stack” of layers is more reflective than a single layer of guanine with cytoplasm underneath. (A stack of five guanine layers separated by cytoplasm layers reflects more than 80% of incident light at the wavelength for which it is “tuned.”) (c) The color that is most strongly reflected from a platelet depends on the angle at which it is viewed. Explain why this should be so. (You can see these changes in color by examining a herring from different angles. Most of the platelets on these fish are oriented in the same way, so that they are vertical when the fish is swimming.)

35.57 Two thin parallel slits are made in an opaque sheet of film. When a monochromatic beam of light is shone through them at normal incidence, the first bright fringes in the transmitted light occur in air at \( \pm 18.0^\circ \) with the original direction of the light beam on a distant screen when the apparatus is in air. When the apparatus is immersed in a liquid, the same bright fringes now occur at \( \pm 12.6^\circ \). Find the index of refraction of the liquid.

35.58 Red light with wavelength 700 nm is passed through a two-slit apparatus. At the same time, monochromatic visible light with another wavelength passes through the same apparatus. As a result, most of the pattern that appears on the screen is a mixture of two colors; however, the center of the third bright fringe \((m = 3)\) of the red light appears pure red, with none of the other color. What are the possible wavelengths of the second type of visible light? Do you need to know the slit spacing to answer this question? Why or why not?

35.59 In a Young’s two-slit experiment a piece of glass with an index of refraction \( n \) and a thickness \( L \) is placed in front of the upper slit. (a) Describe qualitatively what happens to the interference pattern. (b) Derive an expression for the intensity \( I \) of the light at points on a screen as a function of \( n, L, \) and \( \theta \). Here \( \theta \) is the usual angle measured from the center of the two slits. That is, determine the equation analogous to Eq. (35.14) but that also involves \( L \) and \( n \) for the glass plate. (c) From your result in part (b) derive an expression for the values of \( \theta \) that locate the maxima in the interference pattern [that is, derive an equation analogous to Eq. (35.4)].

35.60 After a laser beam passes through two thin parallel slits, the first completely dark fringes occur at \( \pm 19.0^\circ \) with the original direction of the beam, as viewed on a screen far from the slits. (a) What is the ratio of the distance between the slits to the wavelength of the light illuminating the slits? (b) What is the smallest angle, relative to the original direction of the laser beam, at which the intensity of the light is \( \frac{1}{4} \) the maximum intensity on the screen?

CHALLENGE PROBLEMS

35.61 The index of refraction of a glass rod is 1.48 at \( T = 20.0^\circ \text{C} \) and varies linearly with temperature, with a coefficient of \( 2.50 \times 10^{-5}/\text{C}^\circ \). The coefficient of linear expansion of the glass is \( 5.00 \times 10^{-6}/\text{C}^\circ \). At 20.0°C the length of the rod is 3.00 cm. A Michelson interferometer has this glass rod in one arm, and the rod is being heated so that its temperature increases at a rate of 5.00°C/min. The light source has wavelength \( \lambda = 589 \) nm, and the rod initially is at \( T = 20.0^\circ \text{C} \). How many fringes cross the field of view each minute?

35.62 Figure P35.62 shows an interferometer known as Fresnel’s biprism. The magnitude of the prism angle \( A \) is