* 24–12 Scattering of Light by the Atmosphere

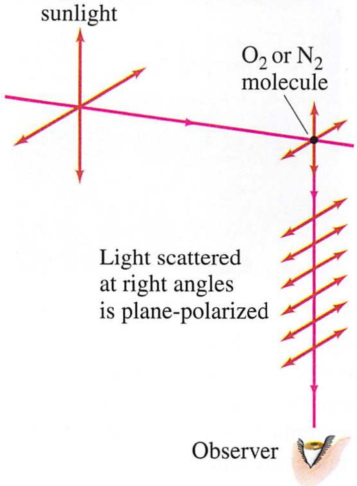

FIGURE 24–54 Unpolarized sunlight scattered by molecules of the air. An observer at right angles sees plane-polarized light, since the component of oscillation along the line of sight emits no light along that line.

Sunsets are red, the sky is blue, and skylight is polarized (at least partially). These phenomena can be explained on the basis of the *scattering* of light by the molecules of the atmosphere. In Fig. 24–54 we see unpolarized light from the Sun impinging on a molecule of the Earth's atmosphere. The electric field of the EM wave sets the electric charges within the molecule into motion, and the molecule absorbs some of the incident radiation. But it quickly reemits this light since the charges are oscillating. As discussed in Section 22–2, oscillating electric charges produce EM waves. The intensity is strongest along a line perpendicular to the oscillation, and drops to zero along the line of oscillation (Section 22–2). In Fig. 24–54 the motion of the charges is resolved into two components. An observer at right angles to the direction of the sunlight, as shown, will see plane-polarized light because no light is emitted along the line of the other component of the oscillation. (When viewing along the line of an oscillation, you don't see that oscillation, and hence see no waves made by it.) At other viewing angles, both components will be present; one will be stronger, however, so the light appears partially polarized. Thus, the process of scattering explains the polarization of skylight.

PHYSICS APPLIED
Why the sky is blue
Why sunsets are red

Scattering of light by the Earth's atmosphere depends on λ. For particles much smaller than the wavelength of light (such as molecules of air), the particles will be less of an obstruction to long wavelengths than to short ones. The scattering decreases, in fact, as $1/\lambda^4$. Blue and violet light are thus scattered much more than red and orange, which is why the sky looks blue. At sunset, the Sun's rays pass through a maximum length of atmosphere. Much of the blue has been taken out by scattering. The light that reaches the surface of the Earth, and reflects off clouds and haze, is thus lacking in blue. That is why sunsets appear reddish.

Why clouds are white

The dependence of scattering on $1/\lambda^4$ is valid only if the scattering objects are much smaller than the wavelength of the light. This is valid for oxygen and nitrogen molecules whose diameters are about 0.2 nm. Clouds, however, contain water droplets or crystals that are much larger than λ. They scatter all frequencies of light nearly uniformly. Hence clouds appear white (or gray, if shadowed).

Summary

The wave theory of light is strongly supported by the observations that light exhibits **interference** and **diffraction**. Wave theory also explains the refraction of light and the fact that light travels more slowly in transparent solids and liquids than it does in air.

An aid to predicting wave behavior is **Huygens' principle**, which states that every point on a wave front can be considered as a source of tiny wavelets that spread out in the forward direction at the speed of the wave itself. The new wave front is the envelope (the common tangent) of all the wavelets.

The wavelength of light in a medium with index of refraction n is

$$\lambda_n = \frac{\lambda}{n}, \tag{24–1}$$

where λ is the wavelength in vacuum; the frequency is not changed.

Young's double-slit experiment clearly demonstrated the interference of light. The observed bright spots of the interference pattern were explained as constructive interference between the beams coming through the two slits, where the beams differ in path length by an integral number of wavelengths. The dark areas in between are due to destructive interference when the path lengths differ by $\frac{1}{2}\lambda$, $\frac{3}{2}\lambda$, and so on. The angles θ at which **constructive interference** occurs are given by

$$\sin\theta = m\frac{\lambda}{d}, \tag{24–2a}$$

where λ is the wavelength of the light, d is the separation of the slits, and m is an integer $(0, 1, 2, \cdots)$. **Destructive interference** occurs at angles θ given by

$$\sin\theta = \left(m + \tfrac{1}{2}\right)\frac{\lambda}{d}, \tag{24–2b}$$

where m is an integer $(0, 1, 2, \cdots)$.

Two sources of light are perfectly **coherent** if the waves leaving them are of the same single frequency and maintain the same phase relationship at all times. If the light waves from the two sources have a random phase with respect to each other over time (as for two incandescent lightbulbs) the two sources are **incoherent**.

The frequency or wavelength of light determines its color. The **visible spectrum** extends from about 400 nm (violet) to about 750 nm (red).

Glass prisms break down white light into its constituent colors because the index of refraction varies with wavelength, a phenomenon known as **dispersion**.

The formula $\sin\theta = m\lambda/d$ for constructive interference also holds for a **diffraction grating**, which consists of many parallel slits or lines, separated from each other by a distance d. The peaks of constructive interference are much brighter and sharper for a diffraction grating than for the simple two-slit apparatus.

A diffraction grating (or a prism) is used in a **spectroscope** to separate different colors or to observe **line spectra**; for a given order m, θ depends on λ. Precise determination of wavelength can be done with a spectroscope by careful measurement of θ.

Diffraction refers to the fact that light, like other waves, bends around objects it passes, and spreads out after passing through narrow slits. This bending gives rise to a **diffraction pattern** due to interference between rays of light that travel different distances.

Light passing through a very narrow slit of width D (on the order of the wavelength λ) will produce a pattern with a bright central maximum of half-width θ given by

$$\sin\theta = \frac{\lambda}{D}, \qquad \textbf{(24–3a)}$$

flanked by fainter lines to either side.

Light reflected from the front and rear surfaces of a thin film of transparent material can interfere. A phase change of 180° ($\frac{1}{2}\lambda$) occurs when the light reflects at a surface where the index of refraction increases. Such **thin-film interference** has many practical applications, such as lens coatings and Newton's rings.

In **unpolarized light**, the electric field vectors oscillate in all transverse directions. If the electric vector oscillates only in one plane, the light is said to be **plane-polarized**. Light can also be partially polarized.

When an unpolarized light beam passes through a **Polaroid** sheet, the emerging beam is plane-polarized. When a light beam is polarized and passes through a Polaroid, the intensity varies as the Polaroid is rotated. Thus a Polaroid can act as a **polarizer** or as an **analyzer**.

The intensity of a plane-polarized light beam incident on a Polaroid is reduced by the factor

$$I = I_0 \cos^2\theta, \qquad \textbf{(24–5)}$$

where θ is the angle between the axis of the Polaroid and the initial plane of polarization.

Light can also be partially or fully **polarized by reflection**. If light traveling in air is reflected from a medium of index of refraction n, the reflected beam will be *completely* plane-polarized if the incident angle θ_p is given by

$$\tan\theta_p = n. \qquad \textbf{(24–6b)}$$

The fact that light can be polarized shows that it must be a transverse wave.

Questions

1. Does Huygens' principle apply to sound waves? To water waves? Explain.

2. What is the evidence that light is energy?

3. Why is light sometimes described as rays and sometimes as waves?

4. We can hear sounds around corners, but we cannot see around corners; yet both sound and light are waves. Explain the difference.

5. If Young's double-slit experiment were submerged in water, how would the fringe pattern be changed?

6. Monochromatic red light is incident on a double slit, and the interference pattern is viewed on a screen some distance away. Explain how the fringe pattern would change if the red light source is replaced by a blue light source.

7. Two rays of light from the same source destructively interfere if their path lengths differ by how much?

8. Why was the observation of the double-slit interference pattern more convincing evidence for the wave theory of light than the observation of diffraction?

9. Compare a double-slit experiment for sound waves to that for light waves. Discuss the similarities and differences.

10. Why doesn't the light from the two headlights of a distant car produce an interference pattern?

11. Suppose white light falls on the two slits of Fig. 24–7, but one slit is covered by a red filter (700 nm) and the other by a blue filter (450 nm). Describe the pattern on the screen.

12. When white light passes through a flat piece of window glass, it is not broken down into colors as it is by a prism. Explain.

13. For both converging and diverging lenses, discuss how the focal length for red light differs from that for violet light.

14. A ray of light is refracted through three different materials (Fig. 24–55). Rank the materials according to their index of refraction, least to greatest.

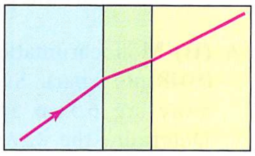

FIGURE 24–55
Question 14.

15. Hold one hand close to your eye and focus on a distant light source through a narrow slit between two fingers. (Adjust your fingers to obtain the best pattern.) Describe the pattern that you see.

16. What happens to the diffraction pattern of a single slit if the whole apparatus is immersed in (*a*) water, (*b*) a vacuum, instead of in air.

17. For diffraction by a single slit, what is the effect of increasing (*a*) the slit width, and (*b*) the wavelength?

18. What is the difference in the interference patterns formed (*a*) by two slits 10^{-4} cm apart, (*b*) by a diffraction grating containing 10^4 lines/cm?

19. For a diffraction grating, what is the advantage of (*a*) many slits, (*b*) closely spaced slits?

20. White light strikes (*a*) a diffraction grating, and (*b*) a prism. A rainbow appears on a wall just below the direction of the horizontal incident beam in each case. What is the color of the top of the rainbow in each case? Explain.

21. For light consisting of wavelengths between 400 nm and 700 nm, incident normally on a diffraction grating, for what orders (if any) would there be overlap in the observed spectrum? Does your answer depend on the slit spacing?

22. Why are interference fringes noticeable only for a *thin* film like a soap bubble and not for a thick piece of glass, say?

23. When a compact disk (CD) is held at an angle in white light, the reflected light is a full spectrum (Fig. 24–56). Explain. What would you expect to see if monochromatic light was used?

FIGURE 24–56 Question 23.

24. Why are Newton's rings (Fig. 24–31) closer together farther from the center?

25. Some coated lenses appear greenish yellow when seen by reflected light. What wavelengths do you suppose the coating is designed to transmit completely?

26. A drop of oil on a pond appears bright at its edges, where its thickness is much less than the wavelengths of visible light. What can you say about the index of refraction of the oil?

27. What does polarization tell us about the nature of light?

28. Explain the advantage of polarized sunglasses over normal tinted sunglasses.

29. How can you tell if a pair of sunglasses is polarizing or not?

30. Two polarized sheets rotated at an angle of 90° with respect to each other will not let any light through. Three polarized sheets, each rotated at an angle of 45° with respect to each other, will let some light through. What will happen to unpolarized light if you align four polarized sheets, each rotated at an angle of 30° with respect to the one in front of it?

* **31.** What would be the color of the sky if the Earth had no atmosphere?

* **32.** If the Earth's atmosphere were 50 times denser than it is, would sunlight still be white, or would it be some other color?

Problems

24–3 Double-Slit Interference

1. (I) Monochromatic light falling on two slits 0.016 mm apart produces the fifth-order fringe at an 8.8° angle. What is the wavelength of the light used?

2. (I) The third-order fringe of 610 nm light is observed at an angle of 18° when the light falls on two narrow slits. How far apart are the slits?

3. (II) Monochromatic light falls on two very narrow slits 0.048 mm apart. Successive fringes on a screen 5.00 m away are 6.5 cm apart near the center of the pattern. Determine the wavelength and frequency of the light.

4. (II) A parallel beam of light from a He-Ne laser, with a wavelength 656 nm, falls on two very narrow slits 0.060 mm apart. How far apart are the fringes in the center of the pattern on a screen 3.6 m away?

5. (II) Light of wavelength 680 nm falls on two slits and produces an interference pattern in which the fourth-order fringe is 38 mm from the central fringe on a screen 2.0 m away. What is the separation of the two slits?

6. (II) If 720-nm and 660-nm light passes through two slits 0.58 mm apart, how far apart are the second-order fringes for these two wavelengths on a screen 1.0 m away?

7. (II) In a double-slit experiment, it is found that blue light of wavelength 460 nm gives a second-order maximum at a certain location on the screen. What wavelength of visible light would have a minimum at the same location?

8. (II) Water waves having parallel crests 2.5 cm apart pass through two openings 5.0 cm apart in a board. At a point 2.0 m beyond the board, at what angle relative to the "straight-through" direction would there be little or no wave action?

9. (II) Suppose a thin piece of glass is placed in front of the lower slit in Fig. 24–7 so that the two waves enter the slits 180° out of phase (Fig. 24–57). Describe in detail the interference pattern on the screen.

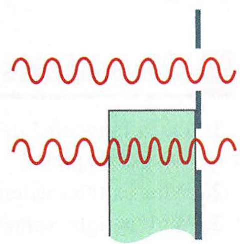

FIGURE 24–57 Problem 9.

10. (II) In a double-slit experiment, the third-order maximum for light of wavelength 500 nm is located 12 mm from the central bright spot on a screen 1.6 m from the slits. Light of wavelength 650 nm is then projected through the same slits. How far from the central bright spot will the second-order maximum of this light be located?

11. (II) Two narrow slits separated by 1.0 mm are illuminated by 544 nm light. Find the distance between adjacent bright fringes on a screen 5.0 m from the slits.

12. (III) Light of wavelength 480 nm in air falls on two slits 6.00×10^{-2} mm apart. The slits are immersed in water, as is a viewing screen 40.0 cm away. How far apart are the fringes on the screen?

13. (III) A very thin sheet of plastic ($n = 1.60$) covers one slit of a double-slit apparatus illuminated by 640-nm light. The center point on the screen, instead of being a maximum, is dark. What is the (minimum) thickness of the plastic?

24–4 Dispersion

14. (I) By what percent, approximately, does the speed of red light (700 nm) exceed that of violet light (400 nm) in silicate flint glass? (See Fig. 24–14.)

15. (II) A light beam strikes a piece of glass at a 60.00° incident angle. The beam contains two wavelengths, 450.0 nm and 700.0 nm, for which the index of refraction of the glass is 1.4820 and 1.4742, respectively. What is the angle between the two refracted beams?

16. (III) A parallel beam of light containing two wavelengths, $\lambda_1 = 450$ nm and $\lambda_2 = 650$ nm, enters the silicate flint glass of an equilateral prism as shown in Fig. 24–58. At what angle does each beam leave the prism (give angle with normal to the face)?

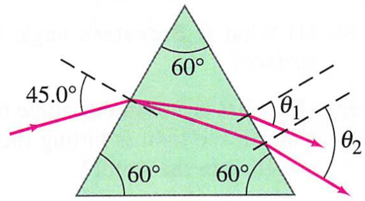

FIGURE 24–58 Problems 16 and 87.

24–5 Single-Slit Diffraction

17. (I) If 580-nm light falls on a slit 0.0440 mm wide, what is the full angular width of the central diffraction peak?

18. (I) Monochromatic light falls on a slit that is 2.60×10^{-3} mm wide. If the angle between the first dark fringes on either side of the central maximum is 35.0° (dark fringe to dark fringe), what is the wavelength of the light used?

19. (II) Light of wavelength 520 nm falls on a slit that is 3.20×10^{-3} mm wide. Estimate how far the first brightish diffraction fringe is from the strong central maximum if the screen is 10.0 m away.

20. (II) A single slit 1.0 mm wide is illuminated by 450-nm light. What is the width of the central maximum (in cm) in the diffraction pattern on a screen 5.0 m away?

21. (II) Monochromatic light of wavelength 653 nm falls on a slit. If the angle between the first bright fringes on either side of the central maximum is 32°, estimate the slit width.

22. (II) How wide is the central diffraction peak on a screen 2.30 m behind a 0.0348-mm-wide slit illuminated by 589-nm light?

23. (II) When blue light of wavelength 440 nm falls on a single slit, the first dark bands on either side of center are separated by 55.0°. Determine the width of the slit.

24. (II) When violet light of wavelength 415 nm falls on a single slit, it creates a central diffraction peak that is 9.20 cm wide on a screen that is 2.55 m away. How wide is the slit?

25. (II) If a slit diffracts 650-nm light so that the diffraction maximum is 4.0 cm wide on a screen 1.50 m away, what will be the width of the diffraction maximum for light of wavelength 420 nm?

26. (II) For a given wavelength λ, what is the maximum slit width for which there will be no diffraction minima?

24–6 and 24–7 Gratings

27. (I) At what angle will 560-nm light produce a second-order maximum when falling on a grating whose slits are 1.45×10^{-3} cm apart?

28. (I) A 3500-line/cm grating produces a third-order fringe at a 28.0° angle. What wavelength of light is being used?

29. (II) How many lines per centimeter does a grating have if the third-order occurs at an 18.0° angle for 630-nm light?

30. (II) A grating has 8300 lines/cm. How many complete spectral orders can be seen (400 nm to 700 nm) when it is illuminated by white light?

31. (II) The first-order line of 589-nm light falling on a diffraction grating is observed at a 15.5° angle. How far apart are the slits? At what angle will the third order be observed?

32. (II) A diffraction grating has 6.0×10^5 lines/m. Find the angular spread in the second-order spectrum between red light of wavelength 7.0×10^{-7} m and blue light of wavelength 4.5×10^{-7} m.

33. (II) Light falling normally on a 9700-line/cm grating is revealed to contain three lines in the first-order spectrum at angles of 31.2°, 36.4°, and 47.5°. What wavelengths are these?

34. (II) What is the highest spectral order that can be seen if a grating with 6000 lines per cm is illuminated with 633-nm laser light? Assume normal incidence.

35. (II) Two (and only two) full spectral orders can be seen on either side of the central maximum when white light is sent through a diffraction grating. What is the maximum number of lines per cm for the grating?

36. (II) White light containing wavelengths from 410 nm to 750 nm falls on a grating with 8500 lines/cm. How wide is the first-order spectrum on a screen 2.30 m away?

37. (II) A He-Ne gas laser which produces monochromatic light of a known wavelength $\lambda = 6.328 \times 10^{-7}$ m is used to calibrate a reflection grating in a spectroscope. The first-order diffraction line is found at an angle of 21.5° to the incident beam. How many lines per meter are there on the grating?

38. (II) Two first-order spectrum lines are measured by a 9500-line/cm spectroscope at angles, on each side of center, of +26°38′, +41°08′ and −26°48′, −41°19′. What are the wavelengths?

24–8 Thin-Film Interference

39. (I) If a soap bubble is 120 nm thick, what wavelength is most strongly reflected at the center of the outer surface when illuminated normally by white light? Assume that $n = 1.34$.

40. (I) How far apart are the dark fringes in Example 24–8 if the glass plates are each 26.5 cm long?

41. (II) What is the smallest thickness of a soap film ($n = 1.42$) that would appear black if illuminated with 480-nm light? Assume there is air on both sides of the soap film.

42. (II) A lens appears greenish yellow ($\lambda = 570$ nm is strongest) when white light reflects from it. What minimum thickness of coating ($n = 1.25$) do you think is used on such a glass ($n = 1.52$) lens, and why?

43. (II) A total of 31 bright and 31 dark Newton's rings (not counting the dark spot at the center) are observed when 550-nm light falls normally on a planoconvex lens resting on a flat glass surface (Fig. 24–31). How much thicker is the center than the edges?

44. (II) A fine metal foil separates one end of two pieces of optically flat glass, as in Fig. 24–33. When light of wavelength 670 nm is incident normally, 28 dark lines are observed (with one at each end). How thick is the foil?

45. (II) How thick (minimum) should the air layer be between two flat glass surfaces if the glass is to appear bright when 450-nm light is incident normally? What if the glass is to appear dark?

46. (II) A piece of material, suspected of being a stolen diamond ($n = 2.42$), is submerged in oil of refractive index 1.43 and illuminated by unpolarized light. It is found that the reflected light is completely polarized at an angle of 59°. Is it diamond?

47. (III) A thin film of alcohol ($n = 1.36$) lies on a flat glass plate ($n = 1.51$). When monochromatic light, whose wavelength can be changed, is incident normally, the reflected light is a minimum for $\lambda = 512$ nm and a maximum for $\lambda = 640$ nm. What is the minimum thickness of the film?

48. (III) When a Newton's ring apparatus (Fig. 24–31) is immersed in a liquid, the diameter of the eighth dark ring decreases from 2.92 cm to 2.48 cm. What is the refractive index of the liquid?

* 24–9 Michelson Interferometer

* 49. (II) What is the wavelength of the light entering an interferometer if 644 bright fringes are counted when the movable mirror moves 0.225 mm?

* 50. (II) A micrometer is connected to the movable mirror of an interferometer. When the micrometer is tightened down on a thin metal foil, the net number of bright fringes that move, compared to the empty micrometer, is 272. What is the thickness of the foil? The wavelength of light used is 589 nm.

* 51. (II) How far must the mirror M_1 in a Michelson interferometer be moved if 850 fringes of 589-nm light are to pass by a reference line?

* 52. (III) One of the beams of an interferometer (Fig. 24–59) passes through a small glass container containing a cavity 1.30 cm deep. When a gas is allowed to slowly fill the container, a total of 236 dark fringes are counted to move past a reference line. The light used has a wavelength of 610 nm. Calculate the index of refraction of the gas, assuming that the interferometer is in vacuum.

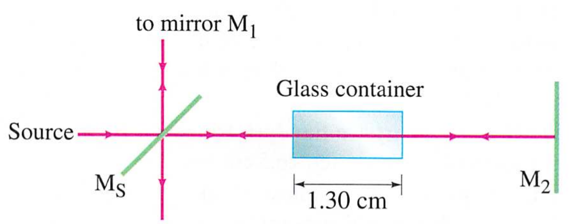

FIGURE 24–59 Problem 52.

24–10 Polarization

53. (I) Two polarizers are oriented at 65° to one another. Unpolarized light falls on them. What fraction of the light intensity is transmitted?

54. (I) What is Brewster's angle for an air–glass ($n = 1.52$) surface?

55. (II) What is Brewster's angle for a diamond submerged in water if the light is hitting the diamond ($n = 2.42$) while traveling in the water?

56. (II) Two Polaroids are aligned so that the light passing through them is a maximum. At what angle should one of them be placed so that the intensity is subsequently reduced by half?

57. (II) At what angle should the axes of two Polaroids be placed so as to reduce the intensity of the incident unpolarized light to (*a*) $\frac{1}{3}$, (*b*) $\frac{1}{10}$?

58. (II) Two polarizers are oriented at 40° to each other and plane-polarized light is incident on them. If only 15% of the light gets through both of them, what was the initial polarization direction of the incident light?

59. (II) Two polarizers are oriented at 38.0° to one another. Light polarized at a 19.0° angle to each polarizer passes through both. What percent reduction in intensity takes place?

60. (II) What would Brewster's angle be for reflections off the surface of water for light coming from beneath the surface? Compare to the angle for total internal reflection, and to Brewster's angle from above the surface.

61. (II) Unpolarized light passes through five successive Polaroid sheets, each of whose axis makes a 45° angle with the previous one. What is the intensity of the transmitted beam?

General Problems

62. Light of wavelength 5.0×10^{-7} m passes through two parallel slits and falls on a screen 4.0 m away. Adjacent bright bands of the interference pattern are 2.0 cm apart. (*a*) Find the distance between the slits. (*b*) The same two slits are next illuminated by light of a different wavelength, and the fifth-order minimum for this light occurs at the same point on the screen as the fourth-order minimum for the previous light. What is the wavelength of the second source of light?

63. Television and radio waves reflecting from mountains or airplanes can interfere with the direct signal from the station. (*a*) What kind of interference will occur when 75-MHz television signals arrive at a receiver directly from a distant station, and are reflected from a nearby airplane 118 m directly above the receiver? Assume $\frac{1}{2}\lambda$ change in phase of the signal upon reflection. (*b*) What kind of interference will occur if the plane is 22 m closer to the receiver?

64. Red light from three separate sources passes through a diffraction grating with 3.00×10^5 lines/m. The wavelengths of the three lines are 6.56×10^{-7} m (hydrogen), 6.50×10^{-7} m (neon), and 6.97×10^{-7} m (argon). Calculate the angles for the first-order diffraction lines of each of these sources.

65. Light of wavelength 590 nm passes through two narrow slits 0.60 mm apart. The screen is 1.70 m away. A second source of unknown wavelength produces its second-order fringe 1.33 mm closer to the central maximum than the 590-nm light. What is the wavelength of the unknown light?

66. A radio station operating at 102.1 MHz broadcasts from two identical antennae at the same elevation but separated by an 8.0-m horizontal distance *d*, Fig. 24–60. A maximum signal is found along the midline, perpendicular to *d* at its midpoint and extending horizontally in both directions. If the midline is taken as 0°, at what other angle(s) θ is a maximum signal detected? A minimum signal? Assume all measurements are made much farther than 8.0 m from the antenna towers.

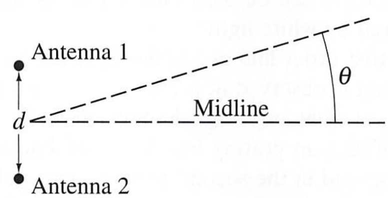

FIGURE 24–60 Problem 66.

67. A teacher stands well back from an outside doorway 0.88 m wide, and blows a whistle of frequency 750 Hz. Ignoring reflections, estimate at what angle(s) it is *not* possible to hear the whistle clearly on the playground outside the doorway.

68. If parallel light falls on a single slit of width D at a 30° angle to the normal, describe the diffraction pattern.

69. The wings of a certain beetle have a series of parallel lines across them. When normally incident 460-nm light is reflected from the wing, the wing appears bright when viewed at an angle of 51°. How far apart are the lines?

70. How many lines per centimeter must a grating have if there is to be no second-order spectrum for any visible wavelength?

71. Show that the second- and third-order spectra of white light produced by a diffraction grating always overlap. What wavelengths overlap exactly?

72. When yellow sodium light, $\lambda = 589$ nm, falls on a diffraction grating, its first-order peak on a screen 60.0 cm away falls 3.32 cm from the central peak. Another source produces a line 3.71 cm from the central peak. What is the wavelength of the new source? How many lines/cm are on the grating?

73. Light is incident on a diffraction grating with 8600 lines/cm, and the pattern is viewed on a screen 2.5 m from the grating. The incident light beam consists of two wavelengths, $\lambda_1 = 4.6 \times 10^{-7}$ m and $\lambda_2 = 6.8 \times 10^{-7}$ m. Calculate the linear distance between the first-order bright fringes of these two wavelengths on the screen.

74. What is the index of refraction of a clear material if a minimum of 150 nm thickness of it, when laid on glass, is needed to reduce reflection to nearly zero when light of 600 nm is incident normally upon it? Do you have a choice for an answer?

75. Monochromatic light of variable wavelength is incident normally on a thin sheet of plastic film in air. The reflected light is a minimum only for $\lambda = 512$ nm and $\lambda = 640$ nm in the visible spectrum. What is the thickness of the film ($n = 1.58$)? [*Hint*: assume successive values of m.]

76. Compare the minimum thickness needed for an anti-reflective coating ($n = 1.38$) applied to a glass lens in order to eliminate (*a*) blue (450 nm), or (*b*) red (700 nm) reflections for light at normal incidence.

77. What is the minimum (non-zero) thickness for the air layer between two flat glass surfaces if the glass is to appear dark when 640-nm light is incident normally? What if the glass is to appear bright?

78. Suppose you viewed the light *transmitted* through a thin film layered on a flat piece of glass. Draw a diagram, similar to Fig. 24–30 or 24–36, and describe the conditions required for maxima and minima. Consider all possible values of index of refraction. Discuss the relative size of the minima compared to the maxima and to zero.

79. At what angle above the horizon is the Sun when light reflecting off a smooth lake is polarized most strongly?

80. At what angle should the axes of two Polaroids be placed so as to reduce the intensity of the incident unpolarized light by an additional factor (after the first Polaroid cuts it in half) of (*a*) 4, (*b*) 10, (*c*) 100?

81. Unpolarized light falls on two polarizer sheets whose transmission axes are at right angles. A third polarizer is placed between the first two so that its axis makes a 62° angle with the axis of the first polarizer. (*a*) What fraction of the incident light intensity is transmitted? (*b*) What if the third polarizer is in front of the other two?

82. Four polarizers are placed in succession with their axes vertical, at 30° to the vertical, at 60° to the vertical, and at 90° to the vertical. (*a*) Calculate what fraction of the incident unpolarized light is transmitted by the four polarizers. (*b*) Can the transmitted light be *decreased* by removing one of the polarizers? If so, which one? (*c*) Can the transmitted light intensity be extinguished by removing polarizers? If so, which one(s)?

83. A laser beam passes through a slit of width 1.0 cm and is pointed at the Moon, which is approximately 380,000 km from the Earth. Assume the laser emits waves of wavelength 630 nm (the red light of a He-Ne laser). Estimate the width of the beam when it reaches the Moon.

84. A series of polarizers are each placed at a 10° interval from the previous polarizer. Unpolarized light is incident on this series of polarizers. How many polarizers does the light have to go through before it is $\frac{1}{4}$ of its original intensity?

85. A thin film of soap ($n = 1.34$) coats a piece of flat glass ($n = 1.52$). How thick is the film if it reflects 643-nm red light most strongly when illuminated normally by white light?

86. Consider two antennas radiating 6.0-MHz radio waves in phase with each other. They are located at points S_1 and S_2, separated by a distance $d = 175$ m, Fig. 24–61. What are the first three points on the y axis where the signals from the two sources will be out of phase (crests of one meet troughs of the other)?

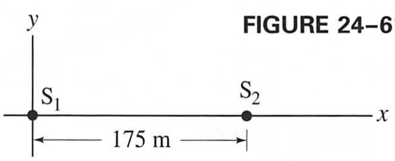

FIGURE 24–61 Problem 86.

87. A parallel beam of light containing two wavelengths, 420 nm and 650 nm, enters a silicate flint glass equilateral prism (Fig. 24–58). (*a*) What is the angle between the two beams leaving the prism? (*b*) Repeat part (*a*) for a diffraction grating with 6200 lines/cm.

* 88. A Lucite planoconvex lens has one flat surface and one with $R = 18.4$ cm. It is used to view an object, located 66.0 cm away from the lens, which is a mixture of red and yellow. The index of refraction of the Lucite is 1.5106 for red light and 1.5226 for yellow light. What are the locations of the red and yellow images formed by the lens? [*Hint*: see Section 23–10.]

Answers to Exercises

A: 2.5 mm.
B: Narrower.
C: 4900 lines/cm.
D: A.
E: Zero for both (*a*) and (*b*), because the two successive polarizers at 90° cancel all light. The 45° Polaroid must be inserted *between* the other two if transmission is to occur.