and

$$\theta = \sin^{-1}\frac{m\lambda}{d}$$

The first bright fringe occurs for $m = 0$ and therefore

$$\theta = \sin^{-1} 0 = 0°$$

That is, the central maximum occurs at $\theta = 0°$, as expected. For $m = 1$, the first-order bright fringe is located at

$$\theta_1 = \sin^{-1}\frac{(1)(500.0 \text{ nm})}{833.0 \text{ nm}} = 36.9°$$

For $m = 2$,

$$\theta_2 = \sin^{-1}\frac{(2)(500.0 \text{ nm})}{833.0 \text{ nm}} = \sin^{-1} 1.20$$

But the sine of θ cannot exceed the value of 1. Yet for $m = 2$, the $\sin\theta = 1.20$, which is impossible. Therefore the second-order bright fringe (corresponding to $m = 2$) does not exist.

The Language of Physics

Diffraction
The bending of light around an obstacle, into the region that should be a shadow area (p. 807).

Monochromatic light
Light that consists of a single wavelength. In contrast, white light consists of light of very many wavelengths. A laser is a good source of monochromatic light (p. 809).

Young's double-slit experiment
An experiment that superimposes light from two different slits to form a series of bright and dark fringes upon a screen. The fringes can only be explained if light has the characteristics associated with waves (p. 809).

Michelson interferometer
An optical device that measures distances or wavelengths very accurately by superimposing light from two different paths to give a series of dark and bright fringes (p. 818).

Thin film
A very thin piece of transparent material. When monochromatic light shines on the film, interference effects can be observed due to a phase change that occurs on reflection and/or a phase change that occurs because of the difference in the optical path of the two interfering light waves (p. 820).

Nonreflecting glass
A piece of glass on which a thin film of transparent material has been placed to cause reflected rays to be out of phase and hence, interfere destructively (p. 823).

Newton's rings
An interference pattern that occurs when light shines on a planoconvex lens that is placed on a flat piece of glass. The pattern consists of a family of concentric dark and bright fringes (p. 828).

Fraunhofer diffraction
Diffraction from a slit in which the source is very far away from the slit, and the slit is very far away from the screen, so that the light waves can be assumed to be plane waves. When the effects of diffraction are combined with the interference of light from a double slit, the resulting intensity distribution is similar to the interference pattern except that the intensity of the fringes decreases farther away from the central bright fringe (p. 829).

Diffraction grating
Several parallel slits of equal width, equally spaced, that gives a characteristic intensity distribution of sharper and narrower fringes (p. 832).

Summary of Important Equations

Equation of plane light wave
$$E = E_0 \sin(kx - \omega t) \quad \textbf{(25.38)}$$

Phase difference in double slit
$$\phi = \frac{2\pi d}{\lambda}\sin\theta \quad \textbf{(28.9)}$$

Resultant wave in double slit
$$E = 2E_0 \cos\left(\frac{\phi}{2}\right)\sin\left(kr_1 - \omega t + \frac{\phi}{2}\right) \quad \textbf{(28.12)}$$

Intensity of an electromagnetic wave
$$I_{avg} = \epsilon_0 c E^2 \quad \textbf{(25.63)}$$

Intensity distribution for a double slit
$$I = \epsilon_0 c 4E_0^2 \cos^2\left(\frac{\phi}{2}\right)\sin^2\left(kr_1 - \omega t + \frac{\phi}{2}\right) \quad \textbf{(28.13)}$$

Average intensity distribution for a double slit
$$I_{avg} = I_0 \cos^2\left(\frac{\phi}{2}\right) \quad \textbf{(28.16)}$$

where
$$I_0 = 2\epsilon_0 c E_0^2 \quad \textbf{(28.15)}$$

Maximum intensity occurs for bright fringe for double slit
$$\frac{\phi}{2} = m\pi \quad \textbf{(28.17)}$$

Condition for bright fringe for double slit
$$d \sin \theta = m\lambda \quad (28.18)$$

Location of mth bright fringe for double slit
$$y_m = \frac{Rm\lambda}{d} \quad (28.21)$$

Minimum intensity for double slit
$$\frac{\phi}{2} = (2m - 1)\frac{\pi}{2} \quad (28.22)$$

Condition for dark fringe for double slit
$$d \sin \theta = (2m - 1)\frac{\lambda}{2} \quad (28.23)$$

Location of mth dark fringe for double slit
$$y_m = (2m - 1)\frac{R\lambda}{2d} \quad (28.24)$$

Michelson interferometer
$$x = m\frac{\lambda}{2} \quad (28.27)$$
$$\lambda = \frac{2x}{m} \quad (28.28)$$

Decreased wavelength in a glass medium
$$\lambda_g = \frac{\lambda_{air}}{n_g} \quad (28.29)$$

Destructive interference for thin film
$$2d = m\frac{\lambda_{air}}{n_w} \quad (28.32)$$

Constructive interference for thin film
$$2d = (2m - 1)\frac{\lambda_{air}}{2n_w} \quad (28.34)$$

Destructive interference for nonreflecting glass
$$2d = (2m - 1)\frac{\lambda_{air}}{2n_{MgF_2}} \quad (28.37)$$

Constructive interference for nonreflecting glass
$$2d = \frac{m\lambda_{air}}{n_{MgF_2}} \quad (28.39)$$

Condition for dark fringe for an air wedge
$$2d = m\lambda \quad (28.40)$$

Location of dark fringe for an air wedge
$$x_m = \frac{m\lambda l}{2h} \quad (28.43)$$

Separation between dark fringes
$$\Delta x = \frac{\lambda l}{2h} \quad (28.44)$$

Condition for bright fringe for an air wedge
$$2d = (2m - 1)\frac{\lambda}{2} \quad (28.45)$$

Location of bright fringe for an air wedge
$$x_m = (2m - 1)\frac{\lambda l}{4h} \quad (28.46)$$

Radius of mth fringe for Newton's rings
$$r_m = \sqrt{m\lambda R} \quad (28.48)$$

Condition for dark fringe for single slit diffraction
$$a \sin \theta = m\lambda \quad (28.51)$$

Condition for bright fringe for diffraction grating
$$d \sin \theta = m\lambda \quad (28.52)$$

Questions for Chapter 28

1. Why do we use monochromatic light rather than white light when doing experiments with interference and diffraction?
2. How can you hear a radio station that is on the other side of the mountain from you?
3. Two separate light sources, such as the headlights of your car, do not cause interference. Why not?
4. What effect does the medium have on interference fringes for (a) light and (b) sound?
5. When destructive interference occurs, what happens to the energy in the light waves?
6. What effect does changing the slit width and the slit separation have on the diffraction pattern?
7. Why don't you observe interference from a thick film, such as an ordinary piece of window glass?
8. Using an audio oscillator, can you set up a double-slit experiment with sound waves? What would the approximate size of the slits have to be? What would you hear on the far side of the double slit?
9. Why are diffraction gratings used more than prisms in spectroscopy?

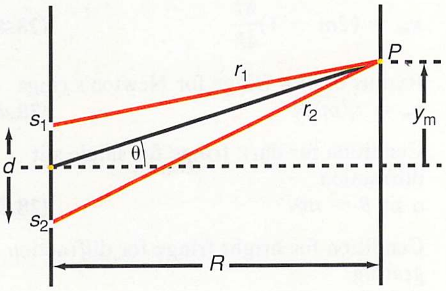
†10. How is the resolving power of a telescope, the smallest resolution of an object that can be determined by the telescope, affected by diffraction?

Problems for Chapter 28

28.2 The Interference of Light—Young's Double-Slit Experiment

1. In a Young's double-slit experiment, a screen is placed 7.00 m behind a double slit of 0.200-mm separation. If light of 589.0 nm shines on the slit, find the value of the angle, θ, corresponding to the first 3 bright fringes.
2. In a Young's double-slit experiment, a screen is placed 5.00 m behind a double slit of 0.250-mm separation. If light of 589.0-nm wavelength shines on the slit, find the value of θ corresponding to the first three dark fringes.
3. In a Young's double-slit experiment, a screen is placed 7.00 m behind a double slit of 0.400-mm separation. If light of 589.0-nm wavelength shines on the slit, find the value of y on the screen corresponding to the first three bright fringes.
4. In a Young's double-slit experiment, a screen is placed 6.00 m behind a double slit of 0.387-mm separation. If light of 589.0-nm wavelength shines on the slit, find the value of y on the screen corresponding to the first three dark fringes.

†5. In a Young's double-slit experiment, a screen is placed 7.00 m behind a double slit of 0.200-mm separation. If light of 589.0-nm wavelength shines on the slit, find (a) the value of the angle θ corresponding to the first three bright fringes, (b) the value of θ corresponding to the first three dark fringes, and (c) the value of y on the screen corresponding to the first three bright and dark fringes.



6. In a double-slit experiment the location of the second bright fringe on the screen is found to be at 12.5 cm. If the distance to the screen is 7.00 m and the separation between slits is 0.176 mm, find the wavelength of the light used.

7. Light of wavelength 600 nm is incident on a double slit whose separation is 0.0480 m. A bright fringe is observed at angular displacement $\theta = 0.0200°$. What is its order (i.e., the value of the integer m)?

8. Adjacent bright fringes from a double slit separated by 0.700 mm are measured to be 1.71 mm apart on a screen 1.00 m away. What is the wavelength of light used?

9. A Young's double-slit experiment is performed with a slit separation of 0.0230 m. A second-order bright fringe is observed at 0.200 mm from the center of the bright central fringe. If the wavelength of the light is 490 nm, find the distance between the double slit and the screen on which the fringes were observed.

10. Show that the distance between bright fringes in a double-slit experiment is equal to the distance between dark fringes.

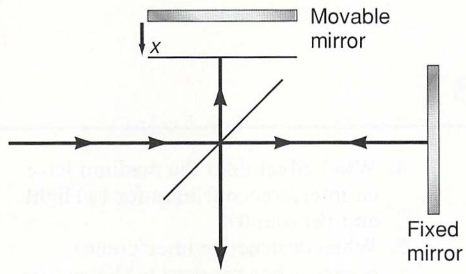
11. What is the distance between fringes in a double-slit experiment when the slit separation is (a) doubled and (b) halved?

28.3 The Interference of Light—The Michelson Interferometer

12. A Michelson interferometer is used to determine the wavelength of a source of light. If the movable mirror moves a distance of 0.250 mm when 800 fringes move across the telescope cross hair, find the wavelength of the light source.

13. A length of 5.00 cm is to be measured very accurately. If a Michelson interferometer is to be used to measure this length, how many fringes of monochromatic light of 589.0-nm wavelengths must pass the cross hair of the telescope to correspond to this length?

14. How far must the movable mirror of the Michelson interferometer be moved in order to observe 900 fringes of light of 589.0-nm wavelength?



†15. A glass tube, 10.0 cm long, is used as one arm of the Michelson interferometer and the standard interference pattern is obtained using a wavelength of light of 589 nm. Water is now slowly introduced into the glass tube. When the tube is full, how many fringes will have passed through the cross hair of the eyepiece?

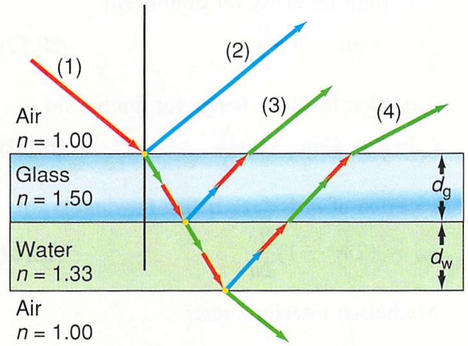
28.4 Interference—Thin Films

16. A light wave of 700 nm passes from air into glass. Find the wavelength of the light in the glass.

17. A light wave has a wavelength of 450 nm in water. Find its wavelength when it enters air.

18. A light wave of 589-nm wavelength in air passes from air into water and then into glass. Find the wavelength of the light in the water and the glass.

19. A wave of light will be reflected and transmitted at the interfaces of the air-glass-water-air surfaces, shown in the diagram. If the thickness of each surface is negligible, find the phase relations between waves 1, 2, 3, and 4.



20. Repeat problem 19 but let the thickness of the water surface equal the thickness of the glass surface, which is equal to half of the incident wavelength of the light in air.

21. Repeat problem 19 but let the thickness of the water surface equal the thickness of the glass surface, which is equal to the incident wavelength of the light in air.

22. Repeat problem 19 but let the thickness of the water surface equal half of the incident wavelength of the light in air and the thickness of the glass surface be equal to the incident wavelength of the light in air.

23. A soap bubble is 200.0 nm thick. For what wavelength of light will (a) the intensity of the reflected light be zero and (b) the intensity of the reflected light be maximum?

24. A soap bubble is 300.0 nm thick. If white light shines on it, what color will it appear in reflected light?

25. The wavelength of the maximum reflected light from a soap bubble is 710 nm. Find the thickness of the soap bubble.

26. What thickness of an oil film ($n = 1.40$) will give complete destructive interference for the reflected light of 589.0-nm wavelength? For this thickness is there any wavelength that will be completely reflected?

27. A thin film of oil of 100-nm thickness lies on a surface. Maximum reflection from the oil occurs for a wavelength in air of 650 nm. Find the index of refraction of the oil.

28. We want to prevent any light of 700.0-nm wavelength from being reflected from a lens. What thickness of magnesium fluoride should be deposited on this lens? For this thickness is there any wavelength of light that gives maximum reflection?

29. If 4% of the incident light is lost by reflection at each lens of a multiple lens optical system, how much light is lost if the system contains six lenses?

30. An air wedge is formed by placing a sheet of paper between the edges of two glass plates 10.0 cm long. If 15 bright fringes are observed per cm, when light of 589.0-nm wavelength shines on the glasses, what is the thickness of the paper?

31. A hair is placed at the edge between two 10.0-cm glass plates of $n = 1.52$. Light of 400-nm wavelength shines on the glass and an interference pattern is formed. If the separation between the second and fourth dark fringe is measured to be 0.800 mm, find the diameter of the hair.

32. Repeat problem 31 but use fused quartz glass ($n = 1.46$) and the glass is immersed in glycerine ($n = 1.47$).

33. Show that the separation distance between bright fringes in an air wedge is equal to the separation distance between dark fringes.

34. Find the equation for the width of a fringe in the interference of light from an air wedge.

35. Newton's rings are used to determine the wavelength of light. If the radius of the fifth fringe is 7.00 mm and the radius of curvature of the lens is measured by a spherometer to be 10.0 m, find the wavelength of light.

36. The radius of the tenth fringe in Newton's rings is 10.0 mm. If the wavelength of light used is 589.0 nm, what is the radius of curvature of the lens?

28.5 Diffraction from a Single Slit

37. In the diffraction from a single slit of width, $a = 15\lambda$, find the angle θ at which the second dark fringe occurs.

38. The first dark fringe for a single slit is found at an angle θ of 5.74° for light of 589.0-nm wavelength. Find the value of the angle θ if the slit width is halved.

39. In a single-slit experiment, the first dark fringe occurs at $\theta = 0.010°$. If the slit is 0.035 m wide, find the wavelength of the light.

40. A source of light of $\lambda = 633$ nm shines on a single slit and a diffraction pattern is found on a wall 1.00 m away. The first dark fringe is found at $x = 5.00$ cm from the central maximum. Find the width of the slit.

41. In a single-slit experiment, a slit 0.0305 m wide receives light of wavelength 640 nm. Find the order of the dark fringe at the angular displacement $\theta = 0.600°$.

28.6 The Diffraction Grating

42. A diffraction grating has 800 lines per mm. Find the distance between each slit.

43. A diffraction grating has 800 lines per mm. If monochromatic light of 589.0-nm wavelength shines on the grating, where will the first three bright fringes be found?

44. How many bright fringes will occur on either side of the central maximum for a diffraction grating of 600 lines per mm if the wavelength of light is 589.0 nm?

45. The first bright fringe of a diffraction grating of 600 lines/mm, is found at an angle of 21.0°. Find the wavelength of light of the source.

46. A first dark fringe is observed at angular displacement $\theta = 15.0°$ due to light of frequency 6.00×10^{14} Hz passing through a diffraction grating. Find the separation of the slits in the grating.

47. Find the longest wavelength that can be observed in second order for a diffraction grating of 800 lines/mm.

48. Using light of 589.0-nm wavelength, a diffraction grating produces a first-order fringe at 44.9°. Find the number of lines/mm of this grating.

Additional Problems

†49. A double-slit experiment is performed with the light source, slits, and screen placed under water. If the separation of the double slit is 0.350 mm, the wavelength of light in air is 589.0 nm, and the screen is 2.00 m away from the slit, find the value of y on the screen corresponding to the third bright fringe.

†50. In a double-slit experiment the intensity of the light on the screen varies from zero at a dark fringe to I_0 at the center of a bright fringe. Find the width of a bright fringe assuming that a bright fringe exists for an intensity of $I \geq 0$.

†51. A piece of flint glass ($n = 1.57$) is being ground into a planoconvex lens. The focal length of the lens is to be 25.0 cm. The radius of curvature of the plane side of the glass is infinite. (a) Find the radius R_1 of the convex side. Newton's rings will be used to verify that the lens has been ground to the correct radius. The lens is placed on a flat piece of glass, and light of 589-nm wavelength illuminates the lens and the characteristic pattern of Newton's rings is obtained. (b) What must be the radius of the fifth fringe such that the lens has the correct focal length?

†52. When two objects are too close together the diffraction pattern of each object can overlap and hence the two objects cannot be seen distinctly. The smallest angular distance between two objects that can be seen distinctly with an optical system is called the resolution of the optical system. The smallest angular resolution is determined by the distance between the central maximum and the first intensity minimum (dark fringe) of the diffraction pattern of the single slit. (Then the two diffraction patterns will not overlap and each object is distinct.) For the single slit discussed in this chapter, the angular separation between the central bright fringe and the dark fringe was determined from $\sin\theta = \lambda/a$. For a circular aperture the result can be shown to be $\sin\theta = 1.22\ \lambda/a$. What is the range of the angular resolution of a human eye if the pupil diameter can vary between 2 and 6 mm, and the wavelength of light used is 550 nm?

53. If the human eye can resolve two objects when the angle between them is 1 minute of arc, how far in advance can you detect two headlights of a car if they are separated by a distance of 1.32 m?

54. A diffraction grating of 1000 lines per cm is to be used for the entire spectrum of visible light. (a) Find the angle of diffraction for the first-order red light (720.0 nm) and first-order blue light (380.0 nm). (b) Find the angular separation. (c) If the screen is placed 1.00 m away, find the linear separation.

55. Calculate the angular separation between the first-order fringes of the two yellow lines in the sodium spectrum, having wavelengths of 589.0 nm and 589.6 nm, for a diffraction grating of 1200 lines/mm.

Interactive Tutorials

56. Young's double-slit intensity. In a double-slit experiment, light of wavelength $\lambda = 589.0$ nm impinges on a double slit that has a separation $d = 0.285$ mm. The screen is placed at a distance $R = 3.50$ m from the double slit. Find the intensity distribution on the screen as a function of the angle θ in figure 28.5.

57. A double slit. In a double-slit experiment, light of wavelength $\lambda = 589.0$ nm impinges on a double slit that has a separation $d = 0.285$ mm. The screen is placed at the distance $R = 3.50$ m from the double slit. Find (a) the value of θ corresponding to the $m = 3$ bright fringe; (b) the value of y locating the *bright* fringe on the screen, as seen in figure 28.5; (c) the value of θ corresponding to the $m = 3$ dark fringe; and (d) the value of y locating the *dark* fringe on the screen.

58. A soap bubble of thickness $d = 300$ nm is illuminated by white light. If the index of refraction of the soap film is $n = 1.28$, calculate (a) the first three wavelengths (lambda) of the incident light that will give a dark fringe and (b) the first three wavelengths of the incident light that will give a bright fringe.

59. A diffraction grating. Monochromatic light of wavelength $\lambda = 589.0$ nm shines on a diffraction grating that has 400 lines per mm. Find (a) the distance d between slits and (b) the value of θ corresponding to the $m = 3$ bright fringe.