CHAPTER 15 Interference and Diffraction

Planning Guide

Compression Guide

To shorten instruction because of time limitations, omit the opener and Section 3 and abbreviate the review.

OBJECTIVES	LABS, DEMONSTRATIONS, AND ACTIVITIES	TECHNOLOGY RESOURCES
PACING • 45 min pp. 524–525 **Chapter Opener**		**CD Visual Concepts,** Chapter 15 BASIC
PACING • 45 min pp. 526–531 **Section 1 Interference** • Describe how light waves interfere with each other to produce bright and dark fringes. • Identify the conditions required for interference to occur. • Predict the location of interference fringes using the equation for double-slit interference.	**TE Demonstration** Interference in Sound Waves, p. 526 BASIC **TE Demonstration** Interference in a Ripple Tank p. 527 BASIC **TE Demonstration** How Distance Traveled Affects Interference, p. 528 ADVANCED **TE Demonstration** Thin-Film Interference, p. 529 BASIC	**OSP Lesson Plans** **TR** 78 Interference Between Transverse Waves **TR** 79 Conditions for Interference of Light Waves **TR** 50A Comparison of Waves in Phase and 180° out of Phase **TR** 51A Path Difference for Light Waves from Two Slits **TR** 52A Position of Higher-Order Interference Fringes
PACING • 135 min pp. 532–540 **Section 2 Diffraction** • Describe how light waves bend around obstacles and produce bright and dark fringes. • Calculate the positions of fringes for a diffraction grating. • Describe how diffraction determines an optical instrument's ability to resolve images.	**SE Skills Practice Lab** Diffraction, pp. 554–555◆ GENERAL **ANC Datasheet** Diffraction* GENERAL **TE Demonstration** Waves Bending Around Corners, p. 532 GENERAL **TE Demonstration** Diffraction and Interference by a Single Slit, p. 533 GENERAL **TE Demonstration** Light Diffraction by an Obstacle: Poisson Spot, p. 534 ADVANCED **TE Demonstration** Effect of Slit Size on Diffraction Patterns, p. 535 GENERAL **TE Demonstration** Multiple-Slit Diffraction p. 536 GENERAL	**OSP Lesson Plans** **TR** 80 Diffraction of Light with Decreasing Slit Width **TR** 81 Constructive Interference by a Diffraction Grating **TR** 82 Function and Use of a Diffraction Grating in a Spectrometer **TR** 83 Resolution of Two Light Sources **TR** 53A Destructive Interference in Single-Slit Diffraction
PACING • 45 min pp. 541–545 *Advanced Level* **Section 3 Lasers** • Describe the properties of laser light. • Explain how laser light has particular advantages in certain applications.	**TE Demonstration** Dancing Light, p. 541 ADVANCED **TE Demonstration** Interference in Laser Light, p. 542 GENERAL	**OSP Lesson Plans** **TR** 84 Operation of a Laser **TR** 85 Components of a Compact Disc Player **TR** 54A Wave Fronts from Noncoherent and Coherent Light Sources

PACING • 90 min

CHAPTER REVIEW, ASSESSMENT, AND STANDARDIZED TEST PREPARATION

- **SE Chapter Highlights,** p. 547
- **SE Chapter Review,** pp. 548–550
- **SE Alternative Assessment,** p. 550 ADVANCED
- **SE Graphing Calculator Practice,** p. 551 GENERAL
- **SE Standardized Test Prep,** pp. 552–553 GENERAL
- **SE Appendix D: Equations,** p. 861
- **SE Appendix I: Additional Problems,** pp. 891
- **ANC Study Guide Worksheet** Mixed Review* GENERAL
- **ANC Chapter Test A*** GENERAL
- **ANC Chapter Test B*** ADVANCED
- **OSP Test Generator**

Online and Technology Resources

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KEY

SE Student Edition
TE Teacher Edition
ANC Ancillary Worksheet
OSP One-Stop Planner
CD CD or CD-ROM
TR Teaching Transparencies
EXT Online Extension
* Also on One-Stop Planner
◆ Requires advance prep

	SKILLS DEVELOPMENT RESOURCES	REVIEW AND ASSESSMENT	CORRELATIONS
			National Science Education Standards
	SE **Sample Set A** Interference, pp. 530–531 GENERAL TE **Classroom Practice,** p. 530 GENERAL ANC **Problem Workbook** Sample Set A* GENERAL OSP **Problem Bank** Sample Set A GENERAL	SE **Section Review,** p. 531 GENERAL ANC **Study Guide Worksheet** Section 1* GENERAL ANC **Quiz** Section 1* BASIC	UCP 1, 2, 3
	SE **Sample Set B** Diffraction Gratings, pp. 537–538 GENERAL TE **Classroom Practice,** p. 537 GENERAL ANC **Problem Workbook** Sample Set B* GENERAL OSP **Problem Bank** Sample Set B GENERAL SE **Conceptual Challenge,** p. 535 ADVANCED	SE **Section Review,** p. 540 GENERAL ANC **Study Guide Worksheet** Section 2* GENERAL ANC **Quiz** Section 2* BASIC	UCP 1, 2, 3, 5 SAI 1, 2 ST 1, 2 HNS 1 SPSP 5
		SE **Section Review,** p. 545 ADVANCED ANC **Study Guide Worksheet** Section 3* ADVANCED ANC **Quiz** Section 3* GENERAL	UCP 1, 2, 3, 5 ST 1, 2 HNS 1 SPSP 5

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Topic: Interference
SciLinks Code: HF60806

Topic: Diffraction
SciLinks Code: HF60405

Topic: Lasers
SciLinks Code: HF60853

Topic: Bar Codes
SciLinks Code: HF60135

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CHAPTER 15
Overview

Section 1 identifies the conditions required for interference to occur and shows how to calculate the location of bright and dark fringes in double-slit interference.

Section 2 describes how diffracted light waves interfere, shows how to calculate the position of fringes produced by a diffraction grating, and discusses the resolving power of optical instruments.

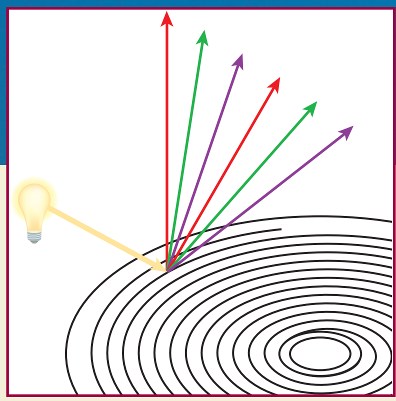
Section 3 describes how a laser produces coherent light and explores applications of lasers.

About the Illustration

The colors visible on the discs' surfaces are characteristic of the light used in the photograph. Have students verify the ability of a compact disc to separate light into its particular spectrum by reflecting light from different sources off a compact disc's surface. For example, sunlight is separated into all of the visible colors, while most fluorescent lighting produces only a few colors.

CHAPTER 15

Interference and Diffraction



The streaks of colored light you see coming from a compact disc resemble the colors that appear when white light passes through a prism. However, the compact disc does not separate light by means of refraction. Instead, the light waves undergo interference.

WHAT TO EXPECT

In this chapter, you will learn about interference of light. In interference, light waves combine to produce resultant waves that are either brighter or less bright than the component waves.

Why it Matters

Devices called *diffraction gratings* use the principle of interference to separate light into its component wavelengths. Diffraction gratings are used in instruments called *spectrometers,* which are used to study the chemical composition and temperature of stars.

CHAPTER PREVIEW

1 Interference
- Combining Light Waves
- Demonstrating Interference

2 Diffraction
- The Bending of Light Waves
- Diffraction Gratings
- Diffraction and Instrument Resolution

3 Lasers
- Lasers and Coherence
- Applications of Lasers

Tapping Prior Knowledge

Knowledge to Review

- ✔ The superposition principle: When two mechanical waves pass through the same space at the same time, their displacements at each point add.
- ✔ When two waves with the same frequency and amplitude overlap, the resulting wave has the same frequency as the individual waves. If the waves are in phase, the resultant wave has twice their amplitude. If they are 180° out of phase, the amplitudes cancel.

Items to Probe

- ✔ Preconceptions about waves: Ask students what happens when two waves (A and B) travel toward each other on a string and meet at a point where A's displacement is 4 cm up and B's displacement is 3 cm up. *(The displacement at that point is 7 cm up.)* What if A is 4 cm up and B is 3 cm down? *(The displacement is 1 cm up.)*

SECTION 1
General Level

Demonstration

Interference in Sound Waves GENERAL

Purpose Introduce students to interference patterns using sound waves from two coherent sources.

Materials sine-wave generator, amplifier, two speakers, tape measures, overhead projector with grid transparency

Procedure Connect the generator and the speakers to the amplifier. Place the speakers about 3 m apart so that both face the class. Have students stand in rows perpendicular to a line joining the two speakers. To reduce the effect of echoes from the walls, have students cover the ear that is opposite the speakers.

Set the generator to a frequency of about 440 Hz. Turn on the generator and amplifier, and adjust the two speakers to equal intensity. Have students slowly walk forward in their rows and listen to the intensity of the sound. Tell them to stand still when they find a location where the sound is at a minimum. Have students measure the distance between each point where sound intensity is at a minimum. Using these data, have students draw the *destructive interference* fringes on the transparency. When all of the fringe positions are recorded, turn the overhead projector on and have students note that they were standing in places where the superposition of waves resulted in destructive interference.

SECTION 1

Interference

SECTION OBJECTIVES

- Describe how light waves interfere with each other to produce bright and dark fringes.
- Identify the conditions required for interference to occur.
- Predict the location of interference fringes using the equation for double-slit interference.

COMBINING LIGHT WAVES

You have probably noticed the bands of color that form on the surface of a soap bubble, as shown in **Figure 1.** Unlike the colors that appear when light passes through a refracting substance, these colors are the result of light waves combining with each other.

Figure 1
Light waves interfere to form bands of color on a soap bubble's surface.

Interference takes place only between waves with the same wavelength

To understand how light waves combine with each other, let us review how other kinds of waves combine. If two waves with identical wavelengths interact, they combine to form a resultant wave. This resultant wave has the same wavelength as the component waves, but according to the superposition principle, its displacement at any instant equals the sum of the displacements of the component waves. The resultant wave is the consequence of the *interference* between the two waves.

Figure 2 can be used to describe pairs of mechanical waves or electromagnetic waves with the same wavelength. A light source that has a single wavelength is called *monochromatic,* which means single colored. In the case of *constructive interference,* the component waves combine to form a resultant wave with the same wavelength but with an amplitude that is greater than the amplitude of either of the individual component waves. For light, the result of constructive interference is light that is brighter than the light from the contributing waves. In the case of *destructive interference,* the resultant amplitude is less than the amplitude of the larger component wave. For light, the result of destructive interference is dimmer light or dark spots.

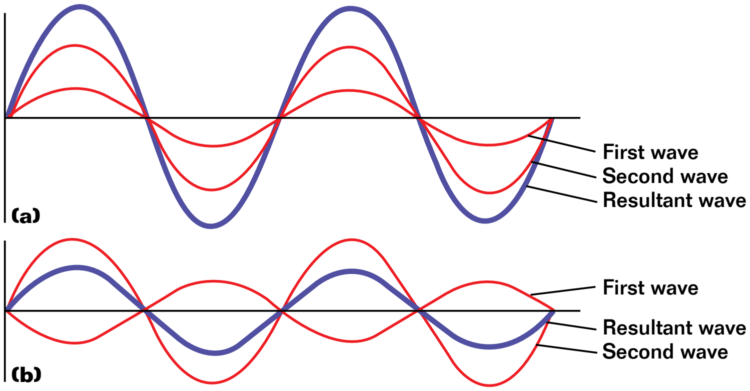


Figure 2
Two waves can interfere **(a)** constructively or **(b)** destructively. In interference, energy is not lost but is instead redistributed.

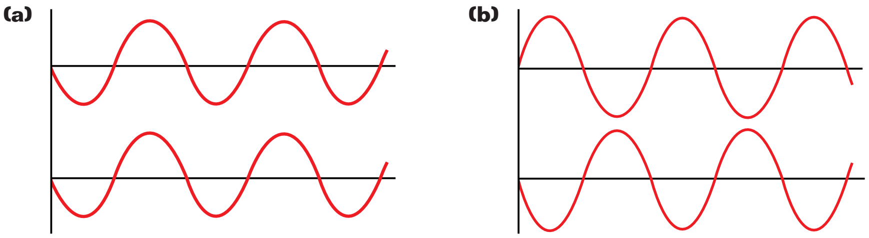


Figure 3
(a) The features of two waves in phase completely match, whereas **(b)** they are opposite each other in waves that are 180° out of phase.

Waves must have a constant phase difference for interference to be observed

For two waves to produce a stable interference pattern, the phases of the individual waves must remain unchanged relative to one another. If the crest of one wave overlaps the crest of another wave, as in **Figure 3(a),** the two have a phase difference of 0° and are said to be *in phase.* If the crest of one wave overlaps the trough of the other wave, as in **Figure 3(b),** the two waves have a phase difference of 180° and are said to be *out of phase.*

Waves are said to have **coherence** when the phase difference between two waves is constant and the waves do not shift relative to each other as time passes. Sources of such waves are said to be *coherent.*

When two light bulbs are placed side by side, no interference is observed, even if the lights are the same color. The reason is that the light waves from one bulb are emitted independently of the waves from the other bulb. Random changes occurring in the light from one bulb do not necessarily occur in the light from the other bulb. Thus, the phase difference between the light waves from the two bulbs is not constant. The light waves still interfere, but the conditions for the interference change with each phase change, and therefore, no single interference pattern is observed. Light sources of this type are said to be *incoherent.*

DEMONSTRATING INTERFERENCE

Interference in light waves from two sources can be demonstrated in the following way. Light from a single source is passed through a narrow slit and then through two narrow parallel slits. The slits serve as a pair of coherent light sources because the waves emerging from them come from the same source. Any random change in the light emitted by the source will occur in the two separate beams at the same time.

If monochromatic light is used, the light from the two slits produces a series of bright and dark parallel bands, or *fringes,* on a distant viewing screen, as shown in **Figure 4.** When the light from the two slits arrives at a point on the viewing screen where constructive interference occurs, a bright fringe appears

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coherence

the correlation between the phases of two or more waves

Figure 4
An interference pattern consists of alternating light and dark fringes.

SECTION 1

Teaching Tip — GENERAL

Point out to students that waves can also interfere in an intermediate way in which the relative phase between the waves is not exactly 0° or 180° as it is in **Figure 2** and **Figure 3.** Ask students to draw waves of the same wavelength that are 45°, 90°, and 135° out of phase. What do the resultant waves look like for each of these three cases?

Demonstration

Interference in a Ripple Tank

Purpose Demonstrate interference patterns using two types of point sources.

Materials ripple tank, ripple generator, two pencils, overhead projector or light source, screen

Procedure Touch the water in the tank with a pencil point several times to generate a wave. Let students observe the wave pattern. Repeat the procedure with two pencils 20 cm apart so that the two waves vary in frequency and phase. Explain that the pencils act as point sources but that they generate waves of different phase or wavelength, or both. Use the ripple generator to create two coherent sources. Point out that the speakers in the previous Demonstration were also coherent sources. Explain that when the sources are coherent, they produce a stable interference pattern.

Demonstration

How Distance Traveled Affects Interference

Purpose Demonstrate that for constructive interference the difference between the distances traveled by two coherent wave fronts is equal to a whole number times the wavelength.

Materials sine-wave generator, amplifier, two speakers, tape measures

Procedure Set up the equipment as in the first Demonstration, and ask students to return to their positions in line. Set the generator to a frequency of about 440 Hz, and ask students to step forward and back until they find a place where the sound is at a maximum. Have them measure the distance from their location to each of the speakers and calculate the difference in distance (path difference). Given the sound's frequency and speed (330 m/s), ask students to calculate its wavelength (*0.75 m*), compare it to the path difference, and record the results on the chalkboard.

Increase the frequency to 660 Hz ($\lambda = 0.50$ m), and repeat the demonstration. Have students notice that they are now standing closer to each other.

Have students examine all the results and note that although each of them has detected a different wave crest, the path difference between the speakers and the wave crest equals a whole number times the wavelength in all cases.

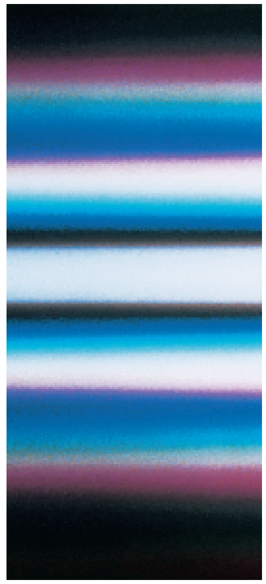


Figure 5
When waves of white light from two coherent sources interfere, the pattern is indistinct because different colors interfere constructively and destructively at different positions.

at that location. When the light from the two slits combines destructively at a point on the viewing screen, a dark fringe appears at that location.

When a white-light source is used to observe interference, the situation becomes more complicated. The reason is that white light includes waves of many wavelengths. An example of a white-light interference pattern is shown in **Figure 5.** The interference pattern is stable or well defined at positions where there is constructive interference between light waves of the same wavelength. This explains the color bands on either side of the center band of white light. This effect also accounts for the bands of color seen on soap bubbles.

Figure 6 shows some of the ways that two coherent waves leaving the slits can combine at the viewing screen. When the waves arrive at the central point of the screen, as in **Figure 6(a),** they have traveled equal distances. Thus, they arrive in phase at the center of the screen, constructive interference occurs, and a bright fringe forms at that location.

When the two light waves combine at a specific point off the center of the screen, as in **Figure 6(b),** the wave from the more distant slit must travel one wavelength farther than the wave from the nearer slit. Because the second wave has traveled exactly one wavelength farther than the first wave, the two waves are in phase when they combine at the screen. Constructive interference therefore occurs, and a second bright fringe appears on the screen.

If the waves meet midway between the locations of the two bright fringes, as in **Figure 6(c),** the first wave travels half a wavelength farther than the second wave. In this case, the trough of the first wave overlaps the crest of the second wave, giving rise to destructive interference. Consequently, a dark fringe appears on the viewing screen between the bright fringes.

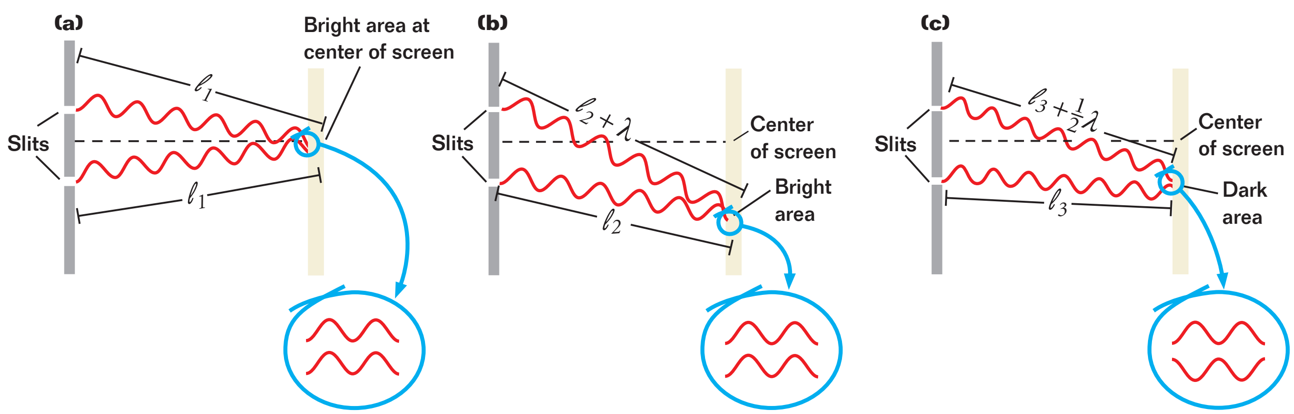


Figure 6
(a) When both waves of light travel the same distance (ℓ_1), they arrive at the screen in phase and interfere constructively. **(b)** If the difference between the distances traveled by the light from each source equals a whole wavelength (λ), the waves still interfere constructively. **(c)** If the distances traveled by the light differ by a half wavelength, the waves interfere destructively.

Predicting the location of interference fringes

Consider two narrow slits that are separated by a distance d, as shown in **Figure 7,** and through which two coherent, monochromatic light waves, l_1 and l_2, pass and are projected onto a screen. If the distance from the slits to the viewing screen is very large compared with the distance between the slits, then l_1 and l_2 are nearly parallel. As a result of this approximation, l_1 and l_2 make the same angle, θ, with the horizontal dotted lines that are perpendicular to the slits. The angle θ also indicates the position at which the waves combine with respect to the central point of the viewing screen.

The difference in the distance traveled by the two waves is called their **path difference.** Study the right triangle shown in **Figure 7,** and note that the path difference between the two waves is equal to $d\sin\theta$. Note carefully that the value for the path difference varies with angle θ and that each value of θ defines a specific position on the screen.

The value of the path difference determines whether the two waves are in or out of phase when they arrive at the viewing screen. If the path difference is either zero or some whole-number multiple of the wavelength, the two waves are in phase, and constructive interference results. The condition for bright fringes (constructive interference) is given by:

EQUATION FOR CONSTRUCTIVE INTERFERENCE

$$d\sin\theta = \pm m\lambda \quad m = 0, 1, 2, 3, \ldots$$

the path difference between two waves = an integer multiple of the wavelength

In this equation, m is the **order number** of the fringe. The central bright fringe at $\theta = 0$ ($m = 0$) is called the *zeroth-order maximum,* or the *central maximum;* the first maximum on either side of the central maximum, which occurs when $m = 1$, is called the *first-order maximum,* and so forth.

Similarly, when the path difference is an odd multiple of $\frac{1}{2}\lambda$, the two waves arriving at the screen are 180° out of phase, giving rise to destructive interference. The condition for dark fringes, or destructive interference, is given by the following equation:

EQUATION FOR DESTRUCTIVE INTERFERENCE

$$d\sin\theta = \pm(m + \tfrac{1}{2})\lambda \quad m = 0, 1, 2, 3, \ldots$$

the path difference between two waves = an odd number of half wavelengths

If $m = 0$ in this equation, the path difference is $\pm\frac{1}{2}\lambda$, which is the condition required for the first dark fringe on either side of the bright central maximum.

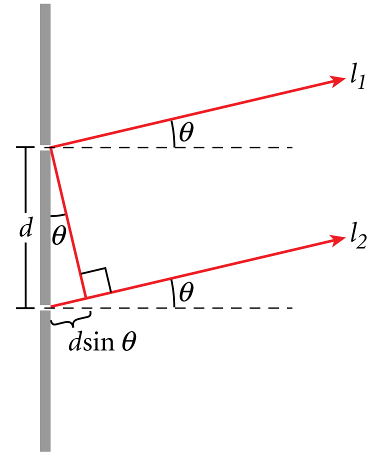


Figure 7
The path difference for two light waves equals $d\sin\theta$. In order to emphasize the path difference, the figure is not drawn to scale.

path difference

the difference in the distance traveled by two beams when they are scattered in the same direction from different points

order number

the number assigned to interference fringes with respect to the central bright fringe

Visual Strategy GENERAL

Figure 7
Point out that lines l_1 and l_2 should intersect for interference to occur. They are represented as parallel only as an approximation so that the path difference can be found mathematically.

Q If $d = 0.50$ mm and $\theta = 0.30°$, how large is the path difference? How many wavelengths does this equal for green light with a wavelength of 520 nm?

A *$d\sin\theta$ = 2600 nm, or 5 wavelengths of the light*

Demonstration

Thin-Film Interference

Purpose Demonstrate that wavelength affects the position of interference fringes.

Materials bottles of soap solution; overhead or slide projector; red, green, and blue cellophane

Procedure Use the soap solution to blow bubbles for the students to observe. Explain that the colors seen on the soap bubble result from interference between two reflected waves. One is reflected from the bubble's outer surface and the other from its inner surface. Because the soap bubble is very thin, the path difference for these waves is so small that interference can be observed. Have students note how the bands of color swirl over the bubbles' surfaces. Cover the light source with one of the pieces of cellophane, and have students repeat the demonstration. This time, have students note the widths of the alternating monochromatic and black bands. After using all three cellophane covers, point out that the fringe width in each pattern varies with color (wavelength).

Visual Strategy – BASIC

Figure 8
Have students notice that the dark and bright fringes form a symmetrical pattern.

Q How many zeroth-order bright lines are there? How many dark ones?

A *one; two*

Classroom Practice

Interference
The distance between two slits is 0.0050 mm. Find the angles of the zeroth-, first-, second-, third-, and fourth-order bright fringes of interference produced with light with a wavelength of 550 nm.

Answer
0°, 6.3°, 13°, 19°, 26°

When monochromatic light falls on two slits with a separation of 0.010 mm, the zeroth-order dark fringes are observed at a 2.0° angle. Find the wavelength.

Answer
7.0×10^{-7} m $= 7.0 \times 10^{2}$ nm

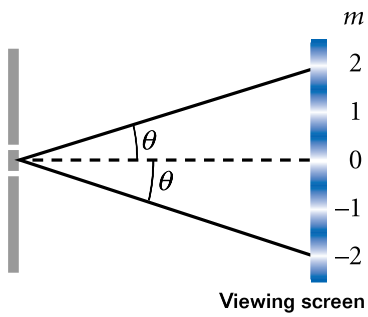


Figure 8
The higher-order ($m = 1, 2$) maxima appear on either side of the central maximum ($m = 0$).

Likewise, if $m = 1$, the path difference is $\pm\frac{3}{2}\lambda$, which is the condition for the second dark fringe on each side of the central maximum, and so forth.

A representation of the interference pattern formed by double-slit interference is shown in **Figure 8.** The numbers indicate the two *maxima* (the plural of *maximum*) that form on either side of the central (zeroth-order) maximum. The darkest areas indicate the positions of the dark fringes, or *minima* (the plural of *minimum*), that also appear in the pattern.

Because the separation between interference fringes varies for light of different wavelengths, double-slit interference provides a method of measuring the wavelength of light. In fact, this technique was used to make the first measurement of the wavelength of light.

SAMPLE PROBLEM A

Interference

PROBLEM

The distance between the two slits is 0.030 mm. The second-order bright fringe ($m = 2$) is measured on a viewing screen at an angle of 2.15° from the central maximum. Determine the wavelength of the light.

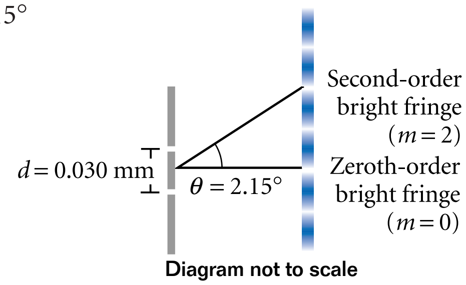
SOLUTION

1. DEFINE

Given: $d = 3.0 \times 10^{-5}$ m $\quad m = 2 \quad \theta = 2.15°$

Unknown: $\lambda = ?$

Diagram:



2. PLAN

Choose an equation or situation: Use the equation for constructive interference.

$$d \sin \theta = m\lambda$$

Rearrange the equation to isolate the unknown:

$$\lambda = \frac{d \sin \theta}{m}$$

3. CALCULATE

Substitute the values into the equation and solve:

$$\lambda = \frac{(3.0 \times 10^{-5}\ \text{m})(\sin 2.15°)}{2}$$

$$\lambda = 5.6 \times 10^{-7}\ \text{m} = 5.6 \times 10^{2}\ \text{nm}$$

$$\boxed{\lambda = 5.6 \times 10^{2}\ \text{nm}}$$

CALCULATOR SOLUTION

Because the minimum number of significant figures for the data is two, the calculator answer 5.627366×10^{-7} should be rounded to two significant figures.

4. EVALUATE

This wavelength of light is in the visible spectrum. The wavelength corresponds to light of a yellow-green color.

PRACTICE A

Interference

1. A double-slit interference experiment is performed with blue-green light from an argon-gas laser (lasers will be discussed further in Section 3). The separation between the slits is 0.50 mm, and the first-order maximum of the interference pattern is at an angle of 0.059° from the center of the pattern. What is the wavelength of argon laser light?

2. Light falls on a double slit with slit separation of 2.02×10^{-6} m, and the first bright fringe is seen at an angle of 16.5° relative to the central maximum. Find the wavelength of the light.

3. A pair of narrow parallel slits separated by a distance of 0.250 mm is illuminated by the green component from a mercury vapor lamp ($\lambda = 546.1$ nm). Calculate the angle from the central maximum to the first bright fringe on either side of the central maximum.

4. Using the data from item 2, determine the angle between the central maximum and the second dark fringe in the interference pattern.

SECTION REVIEW

1. What is the necessary condition for a path length difference between two waves that interfere constructively? destructively?

2. If white light is used instead of monochromatic light to demonstrate interference, how does the interference pattern change?

3. If the distance between two slits is 0.0550 mm, find the angle between the first-order and second-order bright fringes for yellow light with a wavelength of 605 nm.

4. **Interpreting Graphics** Two radio antennas simultaneously transmit identical signals with a wavelength of 3.35 m, as shown in **Figure 9.** A radio several miles away in a car traveling parallel to the straight line between the antennas receives the signals. If the second maximum is located at an angle of 1.28° north of the central maximum for the interfering signals, what is the distance, *d*, between the two antennas?

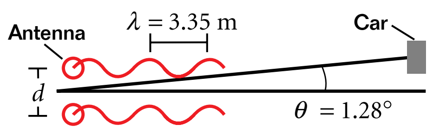


Figure 9

SECTION 1

PROBLEM GUIDE A

Use this guide to assign problems.
SE = Student Edition Textbook
PW = Problem Workbook
PB = Problem Bank on the One-Stop Planner (OSP)

Solving for:

λ	**SE** Sample, 1–2; Ch. Rvw. 9–11, 29 **PW** 3–4 **PB** 4–6
θ	**SE** 3–4 **PW** Sample, 1–2 **PB** 7–10
d	**SE** Ch. Rvw. 28 **PW** 5–7 **PB** Sample, 1–3

***Challenging Problem**
Consult the printed Solutions Manual or the OSP for detailed solutions.

ANSWERS

Practice A

1. 5.1×10^{-7} m $= 5.1 \times 10^2$ nm
2. 574 nm
3. 0.125°
4. 25.2°

SECTION REVIEW ANSWERS

1. a difference of an integral number of wavelengths; a difference of an odd integral number of half wavelengths
2. It becomes blurred, and the bright fringes are made up of narrow, colored bands.
3. 0.63°
4. 3.00×10^2 m

SECTION 2
General Level

Demonstration

Waves Bending Around Corners — GENERAL

Purpose Demonstrate wave diffraction in a ripple tank.

Materials ripple tank, straight-wave generator, barrier, overhead projector or light source, screen

Procedure Place the barrier in the tank, and turn on the straight-wave generator. Let students examine the edges of the "shadow" of quiet water extending beyond the barrier. Explain that the waves that appear to start at the corners illustrate Huygens' principle. Ask students to sketch the patterns that they observe and to describe areas of light and shadow that would be formed if this were a light wave. Point out that the divergence of a wave from its initial path by an obstacle is called diffraction.

SECTION 2

Diffraction

SECTION OBJECTIVES

- **Describe how light waves bend around obstacles and produce bright and dark fringes.**
- **Calculate the positions of fringes for a diffraction grating.**
- **Describe how diffraction determines an optical instrument's ability to resolve images.**

THE BENDING OF LIGHT WAVES

If you stand near the corner of a building, you can hear someone who is talking around the corner, but you cannot see the person. The reason is that sound waves are able to bend around the corner. In a similar fashion, water waves bend around obstacles, such as the barriers shown in **Figure 10.** Light waves can also bend around obstacles, but because of their short wavelengths, the amount they bend is too small to be easily observed.

If light traveled only in straight lines, you would not be able to observe an interference pattern in the double-slit demonstration. Instead, you would see two thin strips of light where each slit and the source were lined up perfectly. The rest of the screen would be completely dark. The edges of the slits would appear on the screen as sharply defined shadows. But this does not happen. Some of the light bends to the right and to the left as it passes through each slit.

The bending of light as it passes through each of the two slits can be understood using Huygens' principle, which states that any point on a wave front can be treated as a point source of waves. Because each slit serves as a point source of light, the waves spread out from the slits. The result is that light deviates from a straight-line path and enters the region that would otherwise be shadowed. This divergence of light from its initial direction of travel is called **diffraction.**

diffraction

a change in the direction of a wave when the wave encounters an obstacle, an opening, or an edge

In general, diffraction occurs when waves pass through small openings, around obstacles, or by sharp edges. When a wide slit (1 mm or more) is placed between a distant light source and a screen, the light produces a bright rectangle with clearly marked edges on the screen. But if the slit is gradually

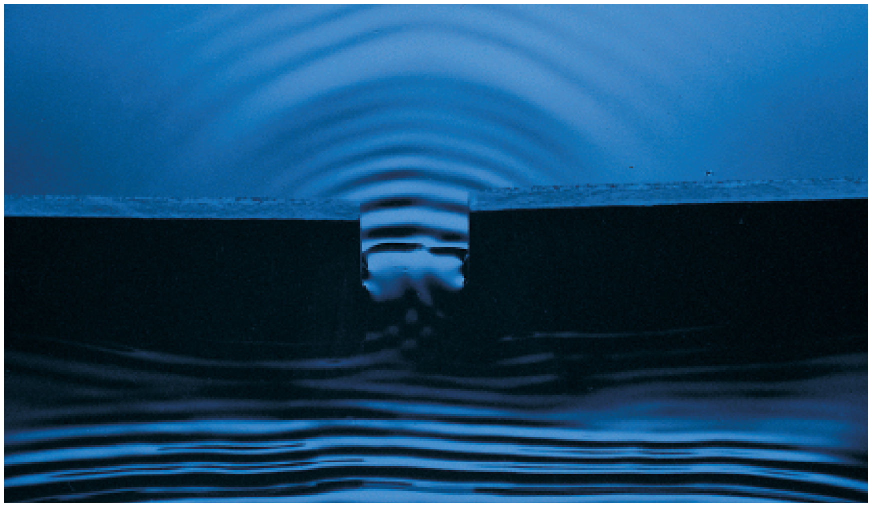


Figure 10
A property of all waves is that they bend, or *diffract*, around objects.

narrowed, the light eventually begins to spread out and produce a *diffraction pattern,* such as that shown in **Figure 11.** Like the interference fringes in the double-slit demonstration, this pattern of light and dark bands arises from the combination of light waves.

Wavelets in a wave front interfere with each other

Diffraction patterns resemble interference patterns because they also result from constructive and destructive interference. In the case of interference, it is assumed that the slits behave as point sources of light. For diffraction, the actual width of a single slit is considered.

According to Huygens' principle, each portion of a slit acts as a source of waves. Hence, light from one portion of the slit can interfere with light from another portion. The resultant intensity of the diffracted light on the screen depends on the angle, θ, through which the light is diffracted.

To understand the single-slit diffraction pattern, consider **Figure 12(a),** which shows an incoming plane wave passing through a slit of width a. Each point (or, more accurately, each infinitely thin slit) within the wide slit is a source of Huygens wavelets. The figure is simplified by showing only five among this infinite number of sources. As with double-slit interference, the viewing screen is assumed to be so far from the slit that the rays emerging from the slit are nearly parallel. At the viewing screen's midpoint, all rays from the slit travel the same distance, so a bright fringe appears.

The wavelets from the five sources can also interfere destructively when they arrive at the screen, as shown in **Figure 12(b).** When the extra distance traveled by the wave originating at point 3 is half a wavelength longer than the wave from point 1, these two waves interfere destructively at the screen. At this same time, the wave from point 5 travels half a wavelength farther than the wave from point 3, so these waves also interfere destructively. With all pairs of points interfering destructively, this point on the screen is dark.

For angles other than those at which destructive interference completely occurs, some of the light waves remain uncanceled. At these angles light appears on the screen as part of a bright band. The brightest band appears in the pattern's center, while the bands to either side are much dimmer.

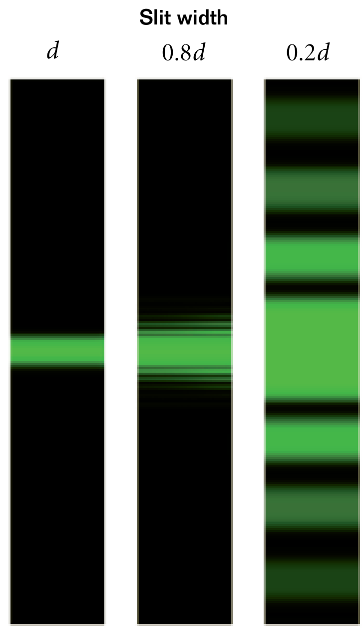


Figure 11
Diffraction becomes more evident as the width of the slit is narrowed. (Note: The wavelength of this light is 510 nm.)

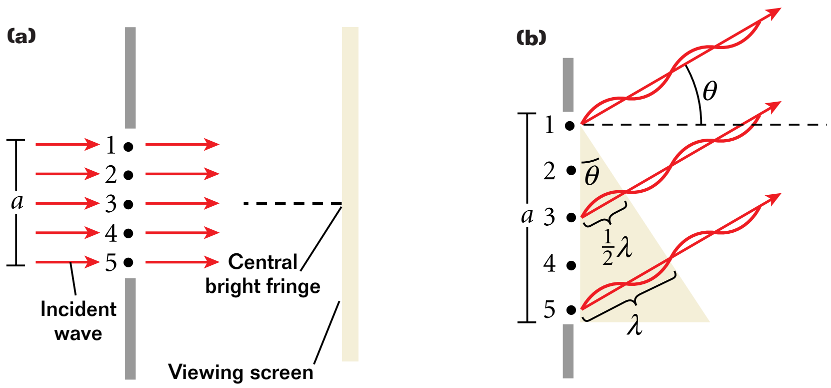


Figure 12
(a) By treating the light coming through the slit as a line of infinitely thin sources along the slit's width, one can determine **(b)** the conditions at which destructive interference occurs between the waves from the upper half of the slit and the waves from the lower half.

Demonstration

Diffraction and Interference by a Single Slit — GENERAL

Purpose Demonstrate diffraction and single-slit interference in a ripple tank.

Materials ripple tank, straight-wave generator, two straight barriers, overhead projector or light source, screen

Procedure Place two barriers about 10 cm from the straight-wave generator, and leave a wide opening between them. Ask students to predict how these obstacles will affect the wave; then, generate the wave to confirm their prediction. Ask what will change when the width of the opening decreases. Have students note that diffraction becomes more evident as the width of the slit narrows.

Tell students that you will increase the wavelength by decreasing the wave generator's frequency until interference patterns appear. (Increase the slit's width, if necessary.) Explain that each portion of the slit acts as a point source. Ask students under what conditions they might expect light to produce similar diffraction and interference patterns (*when the slit is wider—but not vastly wider—than the wavelength*).

Demonstration

Light Diffraction by an Obstacle: Poisson Spot — ADVANCED

Purpose Demonstrate the bright spot of light produced by interference of diffracted light around the edge of an obstacle.

Materials laser, pin with a round head, clay, screen

CAUTION *Direct the laser beam away from the students.*

Procedure Place the pin tip in the clay, and place the pinhead in the path of the laser beam (far enough away that the beam is a little larger than the pinhead). Ask students to describe the pattern they expect to see on the screen. (Some students may expect a dark shadow of the pinhead; others may correctly expect an interference pattern in the shadow due to light bending around the edges of the head.) Have students note the bright spot at the center of the shadow. Explain that this experiment was crucial in confirming the wave theory of light. If light travels in straight-line paths with no bending around obstacles, as it would if light were composed of a stream of particles, the center of the shadow would be dark. The wave theory of light, however, predicts constructive interference will occur at this point producing a bright spot.

SCILINKS. www.scilinks.org
Topic: Diffraction
Code: HF60405

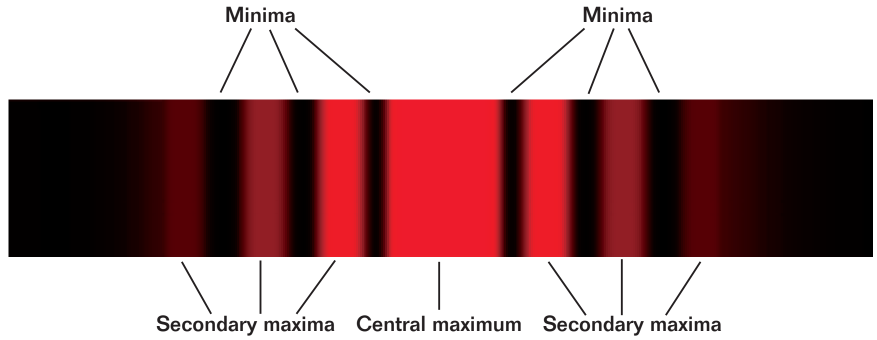


Figure 13
In a diffraction pattern, the central maximum is twice as wide as the secondary maxima.

Light diffracted by an obstacle also produces a pattern

The diffraction pattern that results from monochromatic light passing through a single slit consists of a broad, intense central band—the *central maximum*—flanked by a series of narrower, less intense secondary bands (called *secondary maxima*) and a series of dark bands, or *minima.* An example of such a pattern is shown in **Figure 13.** The points at which maximum constructive interference occurs lie approximately halfway between the dark fringes. Note that the central bright fringe is quite a bit brighter and about twice as wide as the next brightest maximum.

Diffraction occurs around the edges of all objects. **Figure 14** shows the diffraction pattern that appears in the shadow of a penny. The pattern consists of the shadow, with a bright spot at its center, and a series of bright and dark bands of light that continue to the shadow's edge. The penny is large compared with the wavelength of the light, and a magnifying glass is required to observe the pattern.

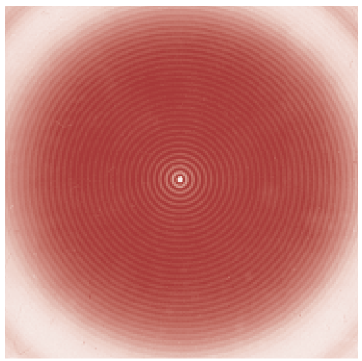


Figure 14
A diffraction pattern forms in the penny's shadow when light is diffracted at the penny's edge. Note the bright spot that is formed at the center of the shadow.

DIFFRACTION GRATINGS

You have probably noticed that if white light is incident on a compact disc, streaks of color are visible. These streaks appear because the digital information (alternating pits and smooth reflecting surfaces) on the disc forms closely spaced rows. These rows of data do not reflect nearly as much light as the thin portions of the disc that separate them. These areas consist entirely of reflecting material, so light reflected from them undergoes constructive interference in certain directions. This constructive interference depends on the direction of the incoming light, the orientation of the disc, and the light's wavelength. Each wavelength of light can be seen at a particular angle with respect to the disc's surface, causing you to see a "rainbow" of color, as shown in **Figure 15.**

Figure 15
Compact discs disperse light into its component colors in a manner similar to that of a diffraction grating.

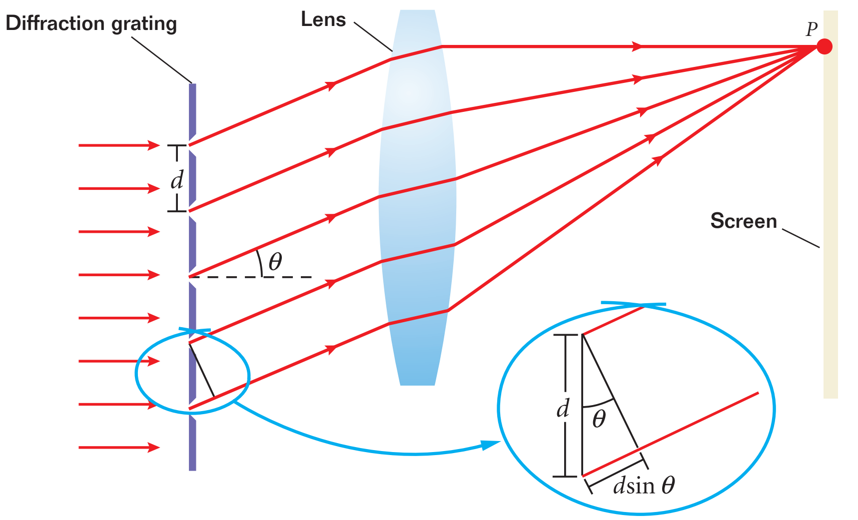


Figure 16
Light of a single wavelength passes through each of the slits of a diffraction grating to constructively interfere at a particular angle θ.

This phenomenon has been put to practical use in a device called a *diffraction grating*. A diffraction grating, which can be constructed to either transmit or reflect light, uses diffraction and interference to disperse light into its component colors with an effect similar to that of a glass prism. A transmission grating consists of many equally spaced parallel slits. Gratings are made by ruling equally spaced lines on a piece of glass using a diamond cutting point driven by an elaborate machine called a *ruling engine*. Replicas are then made by pouring liquid plastic on the grating and then peeling it off once it has set. This plastic grating is then fastened to a flat piece of glass or plastic for support.

Figure 16 shows a schematic diagram of a section of a diffraction grating. A monochromatic plane wave is incoming from the left, normal to the plane of the grating. The waves that emerge nearly parallel from the grating are brought together at a point P on the screen by the lens. The intensity of the pattern on the screen is the result of the combined effects of interference and diffraction. Each slit produces diffraction, and the diffracted beams in turn interfere with one another to produce the pattern.

For some arbitrary angle, θ, measured from the original direction of travel of the wave, the waves must travel *different* path lengths before reaching point P on the screen. Note that the path difference between waves from any two adjacent slits is $d\sin\theta$. If this path difference equals one wavelength or some integral multiple of a wavelength, waves from all slits will be in phase at P, and a bright line will be observed. The condition for bright line formation at angle θ is therefore given by the equation for constructive interference:

$$d\sin\theta = \pm m\lambda \qquad m = 0, 1, 2, 3, \ldots$$

This equation can be used to calculate the wavelength of light if you know the grating spacing and the angle of deviation. The integer m is the order number for the bright lines of a given wavelength. If the incident radiation contains several wavelengths, each wavelength deviates by a specific angle, which can be determined from the equation.

Why it Matters

Conceptual Challenge

1. Spiked Stars

Photographs of stars always show spikes extending from the stars. Given that the aperture of a camera's rectangular shutter has straight edges, explain how diffraction accounts for the spikes.

2. Radio Diffraction

Visible light waves are not observed diffracting around buildings or other obstacles. However, radio waves can be detected around buildings or mountains, even when the transmitter is not visible. Explain why diffraction is more evident for radio waves than for visible light.

Demonstration

Effect of Slit Size on Diffraction Patterns — GENERAL

Purpose Demonstrate that light diffraction is more evident in narrow slits.

Materials two razor blades, clear glass or plastic plate, unfrosted colored light bulb, adhesive tape

Procedure Tape the two razor blades flat on the plate with one blade's edge nearly touching the edge of the other blade. In a dark room, have students stand 3 to 6 m away from the light and look through the slit to observe the diffraction pattern. Ask how the distance from the first dark line to the bright central fringe would vary as the slit's width decreases (*the distance increases*). Point out that the central fringe is wider and much brighter than the others. Explain that diffraction gratings have many very narrow slits, allowing the observer to see the first bright fringe from each slit. (The other ones are less evident.)

ANSWERS — ADVANCED

Conceptual Challenge

1. The edges of the camera shutter diffract light, causing secondary maxima to appear on the sides of the star's image. These maxima give the appearance of light spikes around the star.
2. The wavelength of a radio wave is much longer than that of visible light.

SECTION 2

The Language of Physics

As in double-slit interference, *d* represents the distance between two adjacent slits. Bright lines occur for special values of θ that exist when the path difference from adjacent slits is a whole number of wavelengths ($m = 0, 1, 2, 3$, and so forth).

Demonstration

Multiple-Slit Diffraction

Purpose Demonstrate patterns formed by a diffraction grating and the effect of different grating line separations.

Materials laser, two optical gratings with different grating constants, screen

CAUTION *Avoid directing the laser beam toward the students.*

Procedure Shine the laser beam onto the screen, and place the optical grating directly in front of the beam. Have students note the bright central fringe (the zeroth-order maximum) and the first-order maxima, one on each side of the zeroth-order maximum.

Replace the first optical grating with the second. Ask students why there are differences in the separation between the zeroth-order and first-order maxima produced by each grating. *(Smaller line spacing produces greater separation between the zeroth-order and first-order maxima.)*

Remind students that diffraction is greatest when the size of the openings and the wavelength of waves are of the same order of magnitude.

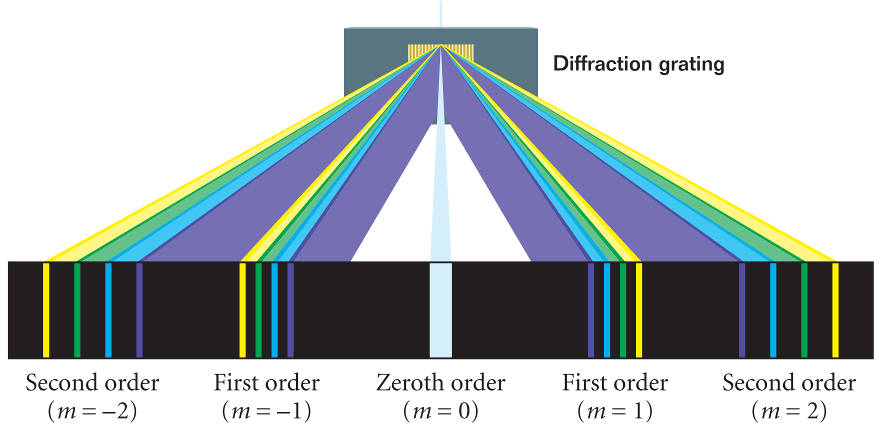


Figure 17
Light is dispersed by a diffraction grating. The angle of deviation for the first-order maximum is smaller for blue light than for yellow light.

Note in **Figure 17** that all wavelengths combine at $\theta = 0$, which corresponds to $m = 0$. This is called the *zeroth-order maximum*. The *first-order maximum,* corresponding to $m = 1$, is observed at an angle that satisfies the relationship $\sin \theta = \lambda/d$. The *second-order maximum*, corresponding to $m = 2$, is observed at an angle where $\sin \theta = 2\lambda/d$.

The sharpness of the principal maxima and the broad range of the dark areas depend on the number of lines in a grating. The number of lines per unit length in a grating is the inverse of the line separation *d*. For example, a grating ruled with 5000 lines/cm has a slit spacing, *d*, equal to the inverse of this number; hence, $d = (1/5000)\ \text{cm} = 2 \times 10^{-4}$ cm. The greater the number of lines per unit length in a grating, the less separation between the slits and the farther spread apart the individual wavelengths of light are.

Diffraction gratings are frequently used in devices called *spectrometers,* which separate the light from a source into its monochromatic components. A diagram of the basic components of a spectrometer is shown in **Figure 18.** The light to be analyzed passes through a slit and is formed into a parallel beam by a lens. The light then passes through the grating. The diffracted light leaves the grating at angles that satisfy the diffraction grating equation. A telescope with a calibrated scale is used to observe the first-order maxima and to measure the angles at which they appear. From these measurements, the wavelengths of the light can be determined and the chemical composition of the light source can be identified. An example of a spectrum produced by a spectrometer is shown in **Figure 19.** Spectrometers are used extensively in astronomy to study the chemical compositions and temperatures of stars, interstellar gas clouds, and galaxies.

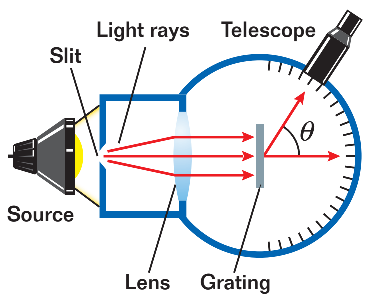


Figure 18
The spectrometer uses a grating to disperse the light from a source.

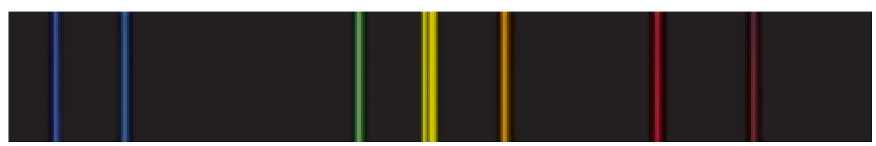


Figure 19
The light from mercury vapor is passed through a diffraction grating, producing the spectrum shown.

SAMPLE PROBLEM B

Diffraction Gratings

PROBLEM

Monochromatic light from a helium-neon laser ($\lambda = 632.8$ nm) shines at a right angle to the surface of a diffraction grating that contains 150 500 lines/m. Find the angles at which one would observe the first-order and second-order maxima.

SOLUTION

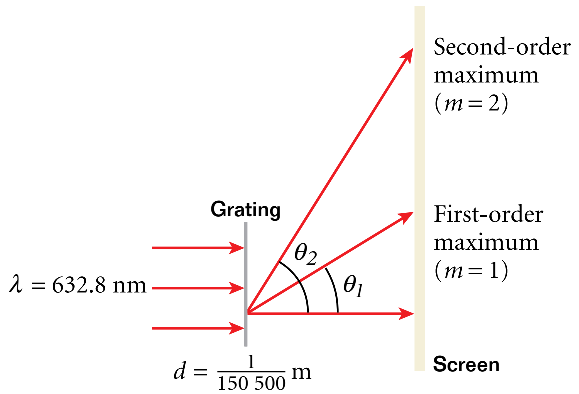
1. DEFINE

Given: $\lambda = 632.8 \text{ nm} = 6.328 \times 10^{-7} \text{ m}$ $\quad m = 1 \text{ and } 2$

$$d = \frac{1}{150\,500 \frac{\text{lines}}{\text{m}}} = \frac{1}{150\,500} \text{ m}$$

Unknown: $\theta_1 = ?$ $\quad \theta_2 = ?$

Diagram:



2. PLAN

Choose an equation or situation: Use the equation for a diffraction grating.

$$d \sin \theta = \pm m\lambda$$

Rearrange the equation to isolate the unknown:

$$\theta = \sin^{-1}\left(\frac{m\lambda}{d}\right)$$

3. CALCULATE

Substitute the values into the equation and solve:

For the first-order maximum, $m = 1$:

$$\theta_1 = \sin^{-1}\left(\frac{\lambda}{d}\right) = \sin^{-1}\left(\frac{6.328 \times 10^{-7} \text{ m}}{\frac{1}{150\,500} \text{ m}}\right)$$

$$\boxed{\theta_1 = 5.465°}$$

continued on next page

SECTION 2

Classroom Practice

Diffraction Gratings

Monochromatic light shines at the surface of a diffraction grating with 5.0×10^3 lines/cm. The first-order maximum is observed at a 15° angle. Find the wavelength.

Answer

5.2×10^2 nm

Find the first-order and the second-order angles of diffraction observed through a 1.00×10^4 lines/cm diffraction grating with light of wavelengths 400.0 nm, 500.0 nm, and 600.0 nm.

Answers

400.0 nm: $\theta_1 = 23.6°$, $\theta_2 = 53.1°$
500.0 nm: $\theta_1 = 30.0°$, $\theta_2 = 90.0°$ (does not occur)
600.0 nm: $\theta_1 = 36.9°$, $\sin\theta_2 = 1.2$ (does not occur)

Light of 400.0 nm wavelength is shined on a 5.0×10^3 lines/cm grating. How many diffraction lines can be observed?

Answer

five ($m = 0, 1, 2, 3, 4$; The $m = 5$ fringe cannot be seen because it is at an angle of 90°.)

SECTION 2

PROBLEM GUIDE B

Use this guide to assign problems.
SE = Student Edition Textbook
PW = Problem Workbook
PB = Problem Bank on the One-Stop Planner (OSP)

Solving for:

θ	**SE** Sample, 1–2; Ch. Rvw. 19–21 **PW** 4–5 **PB** 4–6
λ	**PW** Sample, 1–2 **PB** 7–10
d	**SE** 5*; Ch. Rvw. 28, 30 **PW** 3 **PB** 3–4
m	**SE** 3–4 **PW** 6–7 **PB** Sample, 1–2

***Challenging Problem**
Consult the printed Solutions Manual or the OSP for detailed solutions.

ANSWERS

Practice B

1. 0.02°, 0.04°, 0.11°
2. a. 11.0°
   b. 17.2°
3. 11
4. 1
5. 6.62×10^3 lines/cm

For $m = 2$:

$$\theta_2 = \sin^{-1}\left(\frac{2\lambda}{d}\right)$$

$$\theta_2 = \sin^{-1}\left(\frac{2(6.328 \times 10^{-7}\ \text{m})}{\frac{1}{150\ 500}\ \text{m}}\right)$$

$$\boxed{\theta_2 = 10.98°}$$

CALCULATOR SOLUTION

Because the minimum number of significant figures for the data is four, the calculator answers 5.464926226 and 10.98037754 should be rounded to four significant figures.

4. EVALUATE The second-order maximum is spread slightly more than twice as far from the center as the first-order maximum. This diffraction grating does not have high dispersion, and it can produce spectral lines up to the tenth-order maxima (where $\sin\theta = 0.9524$).

PRACTICE B

Diffraction Gratings

1. A diffraction grating with 5.000×10^3 lines/cm is used to examine the sodium spectrum. Calculate the angular separation of the two closely spaced yellow lines of sodium (588.995 nm and 589.592 nm) in each of the first three orders.

2. A diffraction grating with 4525 lines/cm is illuminated by direct sunlight. The first-order solar spectrum is spread out on a white screen hanging on a wall opposite the grating.

a. At what angle does the first-order maximum for blue light with a wavelength of 422 nm appear?

b. At what angle does the first-order maximum for red light with a wavelength of 655 nm appear?

3. A grating with 1555 lines/cm is illuminated with light of wavelength 565 nm. What is the highest-order number that can be observed with this grating? (Hint: Remember that $\sin\theta$ can never be greater than 1 for a diffraction grating.)

4. Repeat item 3 for a diffraction grating with 15 550 lines/cm that is illuminated with light of wavelength 565 nm.

5. A diffraction grating is calibrated by using the 546.1 nm line of mercury vapor. The first-order maximum is found at an angle of 21.2°. Calculate the number of lines per centimeter on this grating.

DIFFRACTION AND INSTRUMENT RESOLUTION

The ability of an optical system, such as a microscope or a telescope, to distinguish between closely spaced objects is limited by the wave nature of light. To understand this limitation, consider **Figure 20,** which shows two light sources far from a narrow slit. The sources can be taken as two point sources that are not coherent. For example, they could be two distant stars that appear close to each other in the night sky.

If no diffraction occurred, you would observe two distinct bright spots (or images) on the screen at the far right. However, because of diffraction, each source is shown to have a bright central region flanked by weaker bright and dark rings. What is observed on the screen is the resultant from the superposition of two diffraction patterns, one from each source.

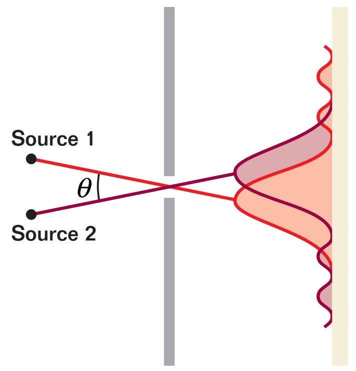


Figure 20
Each of two distant point sources produces a diffraction pattern.

Resolution depends on wavelength and aperture width

If the two sources are separated so that their central maxima do not overlap, as in **Figure 21,** their images can just be distinguished and are said to be barely *resolved.* To achieve high resolution or **resolving power,** the angle between the resolved objects, θ, should be as small as possible as shown in **Figure 20.** The shorter the wavelength of the incoming light or the wider the opening, or *aperture,* through which the light passes, the smaller the angle of resolution, θ, will be and the greater the resolving power will be. For visible-light telescopes, the aperture width, D, is approximately equal to the diameter of the mirror or lens. The equation to determine the limiting angle of resolution *in radians* for an optical instrument with a circular aperture is as follows:

resolving power

the ability of an optical instrument to form separate images of two objects that are close together

$$\theta = 1.22\frac{\lambda}{D}$$

The constant 1.22 comes from the derivation of the equation for circular apertures and is absent for long slits. Note that one radian equals $(180/\pi)°$, as discussed in the Appendix J feature "Angular Kinematics." The equation indicates that for light with a short wavelength, such as an X ray, a small aperture is sufficient for high resolution. On the other hand, if the wavelength of the light is long, as in the case of a radio wave, the aperture must be large in order to resolve distant objects. This is one reason why radio telescopes have large dish-like antennas.

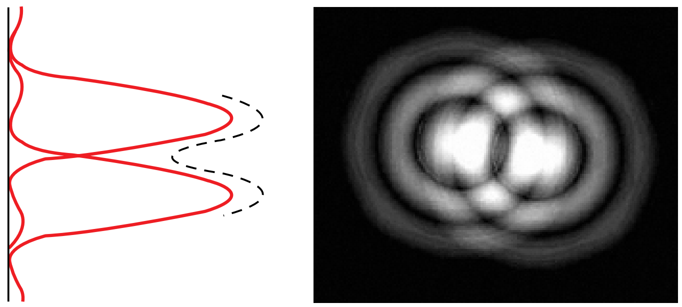


Figure 21
Two point sources are barely resolved if the central maxima of their diffraction patterns do not overlap.

Focus on the Standards

Teaching Physics 4f to Mastery *Students know how to identify the characteristic properties of waves: interference (beats), diffraction, refraction, Doppler effect, and polarization.* **Activity** As a class, review the characteristic properties of waves. Have students find examples of waves they observe in their everyday lives. They should identify the wave, tell which characteristics it demonstrates, and explain why they think this is happening. Each student should present at least one of these to the class.

The Language of Physics — ADVANCED

Point out that the equation for resolving power is known as the Rayleigh criterion. This equation gives the angle θ in *radians.* One rad equals $(180/\pi)°$. For example, for light with a wavelength of 500.0 nm, a lens that is 0.10 m in diameter has a limiting angle of 6.1×10^{-6} rad, or $(3.5 \times 10^{-4})°$. This may seem like a very small angle, but for viewing the surface of Mars (nearly 75×10^6 km away), it corresponds to a distance of about 460 km. This means a telescope with such a lens would show two mountains separated by a distance of less than 460 km as one blurred mountain.

Teaching Tip

Ask which color, blue or red, gives a better resolution with a microscope (*blue, because it has a shorter wavelength*). Point out that electron microscopes allow us to distinguish smaller details in cells than is possible with visible light because the effective wavelength of electrons used in electron microscopes typically is measured in hundredths of a nanometer. This is about 10 000 times shorter than the wavelength of red light.

SECTION REVIEW ANSWERS

1. **a.** 5.89×10^{-7} m (589 nm)
   b. 24.7°
2. The width of the central maximum increases as the width of the slit decreases.
3. a human hair; Its size is closest to the size of the wavelength of visible light.
4. orange light; Longer wavelengths are diffracted more.
5. The image of the point source casts a sharp shadow when the hole is much wider than the light's wavelength. As the hole narrows, the light waves bend more around the hole's edges, causing the image to widen. Light waves from the hole destructively interfere, producing a regular pattern of dark fringes on either side of the bright central fringe.
6. yes; Ultraviolet light has a shorter wavelength than visible light, and resolving power is greater for short wavelengths.

Figure 22
The 27 antennas at the Very Large Array in New Mexico are used together to provide improved resolution for observing distant radio sources. The antennas can be arranged to have the resolving power of a 36 km wide radio telescope.

Yet, even with their large sizes, radio telescopes cannot resolve sources as easily as visible-light telescopes resolve visible-light sources. At the shortest radio wavelength (1 mm), the largest single antenna for a radio telescope—the 305 m dish at Arecibo, Puerto Rico—has a resolution angle of 4×10^{-6} rad. The same resolution angle can be obtained for the longest visible light waves (700 nm) by an optical telescope with a 21 cm mirror.

To compensate for the poor resolution of radio waves, one can combine several radio telescopes so that they will function like a much larger telescope. An example of this is shown in **Figure 22.** If the radio antennas are arranged in a line and computers are used to process the signals that each antenna receives, the resolution of the radio "images" is the same as it would be if the radio telescope had a diameter of several kilometers.

It should be noted that the resolving power for optical telescopes on Earth is limited by the constantly moving layers of air in the atmosphere, which blur the light from objects in space. The images from the *Hubble Space Telescope* are of superior quality largely because the telescope operates in the vacuum of space. Under these conditions, the actual resolving power of the telescope is close to the telescope's theoretical resolving power.

SECTION REVIEW

1. Light passes through a diffraction grating with 3550 lines/cm and forms a first-order maximum at an angle of 12.07°.
   a. What is the wavelength of the light?
   b. At what angle will the second maximum appear?
2. Describe the change in width of the central maximum of the single-slit diffraction pattern as the width of the slit is made smaller.
3. Which object would produce the most distinct diffraction pattern: an apple, a pencil lead, or a human hair? Explain your answer.
4. Would orange light or blue light produce a wider diffraction pattern? Explain why.
5. **Critical Thinking** A point source of light is inside a container that is opaque except for a single hole. Discuss what happens to the image of the point source projected onto a screen as the hole's width is reduced.
6. **Critical Thinking** Would it be easier to resolve nearby objects if you detected them using ultraviolet radiation rather than visible light? Explain.

Lasers

SECTION 3

SECTION OBJECTIVES

- Describe the properties of laser light.
- Explain how laser light has particular advantages in certain applications.

LASERS AND COHERENCE

At this point, you are familiar with electromagnetic radiation that is produced by glowing, or *incandescent,* light sources. This includes light from light bulbs, candle flames, or the sun. You may have seen another form of light that is very different from the light produced by incandescent sources. The light produced by a **laser** has unique properties that make it very useful for many applications.

laser

a device that produces coherent light at a single wavelength

To understand how laser light is different from conventional light, consider the light produced by an incandescent light bulb, as shown in **Figure 23.** When electric charges move through the filament, electromagnetic waves are emitted in the form of visible light. In a typical light bulb, there are variations in the structure of the filament and in the way charges move through it. As a result, electromagnetic waves are emitted at different times from different parts of the filament. These waves have different intensities and move in different directions. The light also covers a wide range of the electromagnetic spectrum because it includes light of different wavelengths. Because so many different wavelengths exist, and because the light is changing almost constantly, the light produced is incoherent. That is, the component waves do not maintain a constant phase difference at all times. The wave fronts of incoherent light are like the wave fronts that result when rain falls on the surface of a pond. No two wave fronts are caused by the same event, and they therefore do not produce a stable interference pattern.

Did you know?

The light from an ordinary electric lamp undergoes about 100 million (10^8) random changes every second.

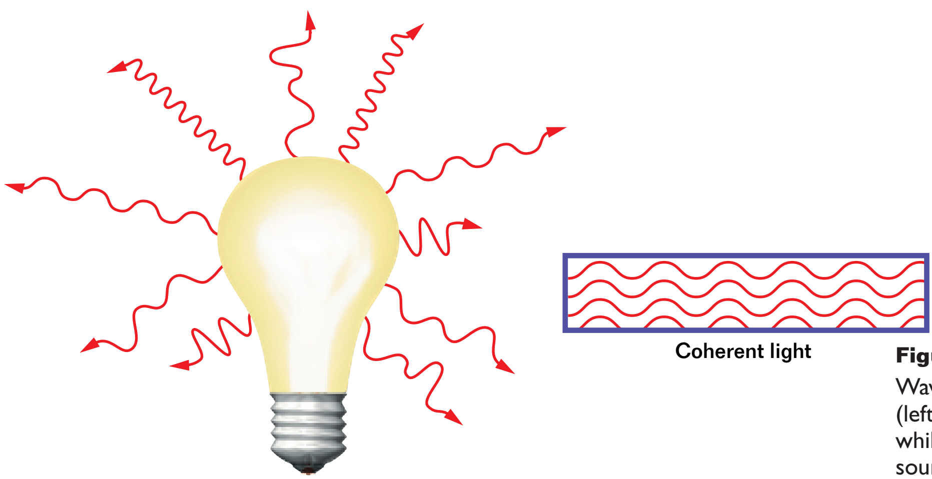


Figure 23
Waves from an incoherent light source (left) have changing phase relationships, while waves from a coherent light source (right) have constant phase relationships.

SECTION 3
Advanced Level

Demonstration

Dancing Light — ADVANCED

Purpose Demonstrate characteristics of a laser beam.

Materials cassette-tape or CD player with an open speaker, clear plastic wrap, reflective polyester film, laser, light pen

CAUTION *Avoid directing the laser beam toward students.*

Procedure Before students arrive, pull the clear wrap tightly around the speaker, and secure it with tape. Tape the reflective film to the clear wrap in front of the speaker. In class, direct the laser beam so that it is reflected off the reflective film attached to the speaker and onto the ceiling. Play the music, and darken the room. Replace the laser with a light pen, and have students compare the two beams. Have them note that laser light is emitted in one narrow beam in one direction and is almost monochromatic.

Demonstration

Interference in Laser Light

GENERAL

Purpose Demonstrate interference of light waves with the same wavelength.

Materials laser, light pen, projection screen, opaque slide with two slits (to make one, spray a layer of paint on a glass plate and use a pin to etch two parallel slits about 1 mm apart through the paint)

CAUTION *Avoid directing the light from the laser at the students.*

Procedure Shine the laser through two slits and project the beam toward the screen. Point out that each slit acts as a point source of light. Have students examine the bands of brightness and darkness. Explain that the areas of darkness correspond to the nodal lines observed in the experiments with sound and water waves in Section 1, in the first two Demonstrations of this chapter.

Repeat the experiment with a light pen. Explain that although the light from the two slits is nearly coherent, white light contains many wavelengths. Although these interfere with each other, the pattern is blurred.

Lasers, on the other hand, typically produce a narrow beam of coherent light. The waves emitted by a laser are in phase, and they do not shift relative to each other as time progresses. Because all the waves are in phase, they interfere constructively at all points. The individual waves effectively behave like a single wave with a very large amplitude. In addition, the light produced by a laser is monochromatic, so all the waves have exactly the same wavelength. As a result of these properties, the intensity, or brightness, of laser light can be made much greater than that of incoherent light. For light, intensity is a measure of the energy transferred per unit time over a given area.

Lasers transform energy into coherent light

A laser is a device that converts light, electrical energy, or chemical energy into coherent light. There are a variety of different types of lasers, but they all have some common features. They all use a substance called the *active medium* to which energy is added to produce coherent light. The active medium can be a solid, liquid, or gas. The composition of the active medium determines the wavelength of the light produced by the laser.

The basic operation of a laser is shown in **Figure 24.** When high-energy light or electrical or chemical energy is added to the active medium, as in **Figure 24(a),** the atoms in the active medium absorb some of the energy. You will learn that atoms exist at different *energy states* in the chapter "Atomic

Did you know?

The word *laser* is an acronym (a word made from the first letters of several words) that stands for "*l*ight *a*mplification by *s*timulated *e*mission of *r*adiation."

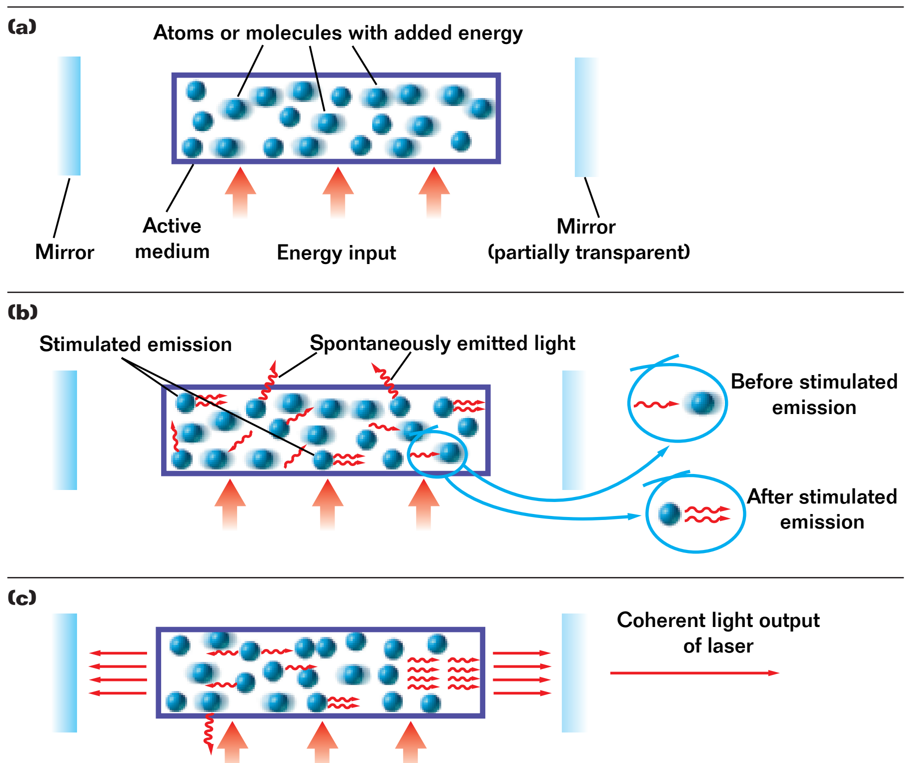


Figure 24
(a) Atoms or molecules in the active medium of a laser absorb energy from an external source. **(b)** When a spontaneously emitted light wave interacts with an atom, it may cause the atom to emit an identical light wave. **(c)** Stimulated emission increases the amount of coherent light in the active medium, and the coherent waves behave as a single wave.

Physics." When energy is added to an atom that is at a lower energy state, the atom can be excited to a higher energy state. These *excited* atoms then release their excess energy in the form of electromagnetic radiation when they return to their original, lower energy states.

When light of a certain wavelength is applied to excited atoms, the atoms can be induced to release light waves that have the same properties. After one atom spontaneously releases its energy in the form of a light wave, this initial wave can cause other energized atoms to release their excess energy as light waves with the same wavelength, phase, and direction as the initial wave, as shown in **Figure 24(b).** This process is called *stimulated emission.*

Most of the light produced by stimulated emission escapes out the sides of the glass tube. However, some of the light moves along the length of the tube, producing more stimulated emission as it goes. Mirrors on the ends of the material return these coherent light waves into the active medium, where they stimulate the emission of more coherent light waves, as shown in **Figure 24(c).** As the light passes back and forth through the active medium, it becomes more and more intense. One of the mirrors is slightly transparent, which allows the intense coherent light to be emitted by the laser.

APPLICATIONS OF LASERS

There are a wide variety of laser types, with wavelengths ranging from the far infrared to the X-ray region of the spectrum. Scientists have also created *masers,* devices similar to lasers but operate in the microwave region of the spectrum. Lasers are used in many ways, from common household uses to a wide variety of industrial uses and very specialized medical applications.

Lasers are used to measure distances with great precision

Of the properties of laser light, the one that is most evident is that it emerges from the laser as a narrow beam. Unlike the light from a light bulb or even the light that is focused by a parabolic reflector, the light from a laser undergoes very little spreading with distance. One reason is that all the light waves emitted by the laser have the same direction. As a result, a laser can be used to measure large distances, because it can be pointed at distant reflectors and the reflected light can be detected.

As shown in **Figure 25,** astronomers direct laser light at particular points on the moon's surface to determine the Earth-to-moon distance. A pulse of light is directed toward one of several 0.25 m^2 reflectors that were placed on the moon's surface by astronauts during the *Apollo* missions. By knowing the speed of light and measuring the time the light takes to travel to the moon and back, scientists have measured the Earth-to-moon distance to be about 3.84×10^5 km. Geologists use repeated measurements to record changes in the height of Earth's crust from geological processes. Lasers can be used for these measurements even when the height changes by only a few centimeters.

Figure 25
A laser beam is fired at reflectors on the moon, which is more than 380 000 km away.

SECTION 3

Key Models and Analogies — GENERAL

Have students think of a busy shopping mall, where people walk in all directions and with different strides. Tell students that this scene can represent incoherent light emitted by a light bulb, with each person being analogous to a light wave with its own direction, wavelength, and phase. Then, have students think of a marching band, with all members of the band lifting their feet at precisely the same time and marching in the same direction with steps that are the same size. Explain that this is analogous to laser light.

STOP Misconception Alert — ADVANCED

Students may think that fluorescence and phosphorescence are related to the way lasers work. Make sure they realize that in fluorescent lamps, any atoms that become excited (by absorbing energy) immediately lose the energy by emitting light. In phosphorescent paint, the excited atoms are able to remain at a higher level of energy for a longer period of time, but they emit light spontaneously. In lasers, most of the atoms remain in an excited state until something triggers the excited atoms to emit light.

Why it Matters

Compact Disc Players

CDs, CD-ROMs, CD-Rs, and DVDs all fall into a class of digital media called *optical storage devices.*

The laser typically used for a CD player has a wavelength of 780 nm, light in the near-infrared region. A DVD player laser has a wavelength of 650 nm, visible as red light. Both of these lasers are diode lasers. These lasers are semiconductor devices that produce low-intensity, coherent light when they carry current.

Why it Matters

Compact Disc Players

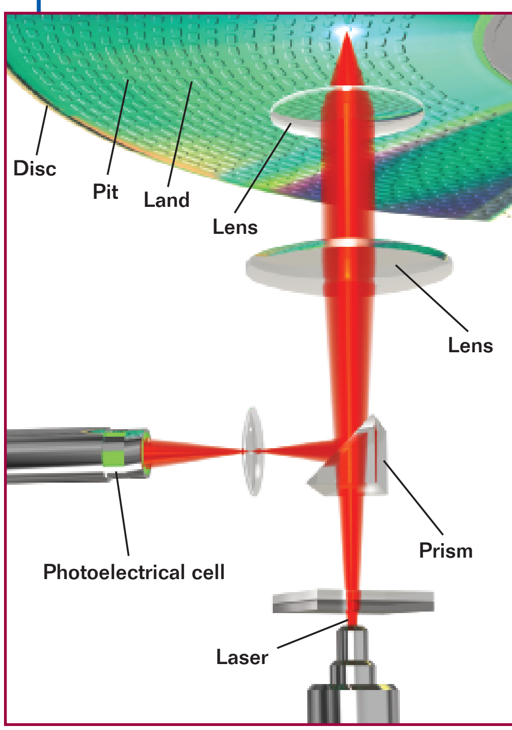
An interesting application of the laser is the compact disc (CD) player. In a CD player, light from a laser is directed through a series of optics toward a compact disc on which the music or data have been digitally recorded. The CD player "reads" the data in the way the laser light is reflected from the compact disc.

In digital recording, a sound signal is sampled at regular intervals of time. Each sampling is converted to an electrical signal, which in turn is converted into a series of binary numbers. Binary numbers consist only of zeros and ones. The binary numbers are coded to contain information about the signal, including the frequencies and harmonics that are present, the volume for the left and right channels, and the speed of the motor that rotates the disc. This process is called *analog-to-digital* (a-d) conversion.

These binary, digital data in a CD are stored as a series of pits and smooth areas (called *lands*) on the surface of the disc. The series of pits and lands is recorded starting at the center of the disc and spiraling outward along *tracks* in the CD. These tracks are just 500 nm wide and spaced 1600 nm apart. If you could stretch the data track of a CD out, it would be almost 5 km long!

When a CD is played, the laser light is reflected off this series of pits and lands into a detector. In fact, the depth of the pit is chosen so that destructive interference occurs when the laser transitions from a pit to a land or from a land to a pit. The detector records the changes in light reflection between the pits and lands as ones and smooth areas as zeros—binary data that are then converted back to the analog signal you hear as music. This step is called *digital-to-analog* (d-a) conversion, and the analog signal can then be amplified to the speaker system.

A CD read-only memory (CD-ROM) drive on your computer works in much the same way. Data from a computer are already in a digital format, so no a-d or d-a conversion is needed.



Light from a laser is directed toward the surface of the compact disc. Smooth parts of the disc reflect the light back to the photoelectrical cell.

You may wonder how a CD-recordable (CD-R) disc is different. These discs don't have any pits and lands at all. Instead, they have a layer of light-sensitive dye sandwiched between a smooth reflective metal, usually aluminum, and clear plastic. A CD-R drive has an additional laser, about 10 times more powerful than a CD reading laser, that writes the digital data along the tracks of the CD-R disc. When the writing laser shines on the light-sensitive dye, the dye turns dark and creates nonreflecting areas along the track. This process creates the digital pattern that behaves like the pits and lands, which a standard CD player can read.

A digital versatile disc (DVD) player operates on the same principle. However, the laser in a DVD player has a shorter wavelength than the laser in a CD player. This shorter wavelength allows the DVD player to read data that are spaced closer together than data on a CD. Additionally, some DVDs contain two layers of data and may even be written on both sides! The lower layer of a two-layer DVD has a thinner coating of reflective material, usually gold, that allows some of the light to pass through it so that the upper level of the DVD can be read.

Lasers have many applications in medicine

Lasers are also used for many medical procedures by making use of the fact that specific body tissues absorb different wavelengths of laser light. For example, lasers can be used to lighten or remove scars and certain types of birthmarks without affecting surrounding tissues. The scar tissue responds to the wavelength of light used in the laser, but other body tissues are protected.

Many medical applications of lasers take advantage of the fact that water can be vaporized by high-intensity infrared light produced by carbon dioxide lasers having a wavelength of 10 μm. Carbon dioxide lasers can cut through muscle tissue by heating and evaporating the water contained in the cells. One advantage of a laser is that the energy from the laser also coagulates blood in the newly opened blood vessels, thereby reducing blood loss and decreasing the risk of infection. A laser beam can also be trapped in an optical fiber endoscope, which can be inserted through an orifice and directed to internal body structures. As a result, surgeons can stop internal bleeding or remove tumors without performing massive surgery.

Lasers can also be used to treat tissues that cannot be reached by conventional surgical methods. For example, some very specific wavelengths of lasers can pass through certain structures at the front of the eye—the cornea and lens—without damaging them. Therefore, lasers can be effective at treating lesions of the retina, inside the eye. Lasers are used for other eye surgeries, including surgery to correct *glaucoma,* a condition in which the fluid pressure within the eye is too great. Left untreated, glaucoma can lead to damage of the optic nerve and eventual blindness. Focusing a laser at the clogged drainage port allows a tiny hole to be burned in the tissue, which relieves the pressure. Lasers can also be used to correct nearsightedness by focusing the beam on the central portion of the cornea to cause it to become flatter.

Did you know?

The principle behind reading the information stored on a compact disc is also the basis for the reading of bar codes found on many products. When these products are scanned, laser light reflected from the bars and spaces of the bar code reproduces the binary codes that represent the product's inventory number. This information is transmitted to the store's computer system, which returns the product's name and price to the cash register.

SCILINKS.
www.scilinks.org
Topic: Bar Codes
Code: HF60135

SECTION REVIEW

1. How does light from a laser differ from light whose waves all have the same wavelength but are not coherent?

2. The process of stimulated emission involves producing a second wave that is identical to the first. Does this gaining of a second wave violate the principle of energy conservation? Explain your answer.

3. **Critical Thinking** Fiber-optic systems transmit light by means of internal reflection within thin strands of extremely pure glass. In these fiber-optic systems, laser light is used instead of white light to transmit the signal. Apply your knowledge of refraction to explain why.

Teaching Tip — ADVANCED

Point out that there are many types of lasers, including semiconductor (diode) lasers, CO_2 lasers, ruby lasers, microwave lasers, X-ray lasers, and tunable lasers. Lasers now have medical, military, industrial, and scientific applications. They are used as bloodless scalpels, saws, and moonquake detectors. Astronomers have even found laser action in stars. In 1996, the *Hubble Space Telescope* discovered an ultraviolet laser star. Have students find more information about how lasers are used, and have them report on one of these topics.

SECTION REVIEW ANSWERS

1. Waves emitted by a laser do not shift relative to each other as time progresses (they are coherent and continuously in phase).
2. no; The second light wave is obtained from the energy that is added to an atom in the active medium by an external energy source.
3. Laser light is nearly monochromatic, so it does not spread out very much into different components with different wavelengths as it passes between the fiber and transmission and receiving equipment (that is, dispersion is nearly absent over short distances).

Laser Surgeon
Dr. Shawn Wong practices ophthalmology in Austin, Texas, and specializes in LASIK (*l*aser-*a*ssisted *i*n *s*itu *k*eratomileusis) surgery to correct vision problems. In his spare time, Dr. Wong enjoys bicycle racing and flying model airplanes.

Dr. Wong particularly likes the problem-solving aspects of his work. He also enjoys "not only making a living, but helping to solve people's problems along the way. Laser eye surgery is a very dynamic field—what we can't do now is just around the corner."

PHYSICS CAREERS

Laser Surgeon

Laser surgery combines two fields—eye care and high-tech engineering—to give perfect vision to people who otherwise would need glasses or contacts. To learn more about this career, read the interview with ophthalmologist Dr. L. Shawn Wong, who runs a laser center in Austin, Texas.

Dr. Wong makes measurements of the eye in preparation for laser surgery.

What sort of education helped you become a laser surgeon?

Besides using my medical school training, I use a lot of engineering in my work; physics and math courses are very helpful. In high school, even in junior high, having a love of math and science is extremely helpful.

Who helped you find your career path?

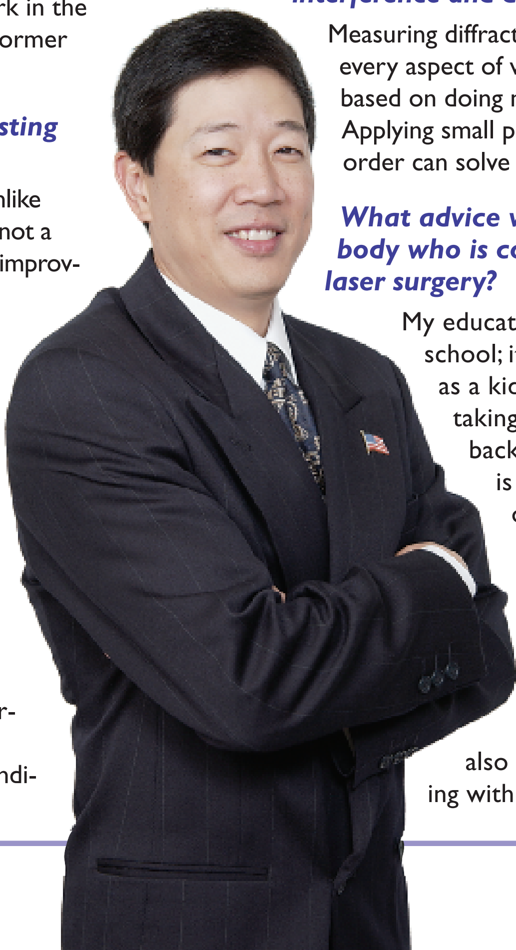
Of all my teachers, my junior high earth science teacher made the biggest impression on me. What I learned in those classes I actually still use today: problem solving. Interestingly, I work in the town where I grew up; a lot of my former teachers are my patients today.

What makes laser surgery interesting to you?

It's nice to be able to help people. Unlike glasses and contacts, laser surgery is not a correction; it's a cure. When you are improving people's vision, everybody in the room gets to see the results. I don't need to tell patients they're doing well—they can tell.

What is the nature of your work?

A typical patient is somebody born with poor vision. We make these patients undergo a lot of formal diagnostic testing and informal screening to be sure they are good candidates. Lasers are used for diagnosing as well as treating. Laser tolerances are extremely small—we're talking in terms of submicrons, the individual cells of the eye.



What is your favorite thing about your job? What would you most like to change about it?

My favorite thing is making people visually free. I would like to be able to solve an even wider range of problems. We can't solve everything.

How does your work relate to the physics of interference and diffraction?

Measuring diffraction and interference is part of every aspect of what we do. The approach is based on doing many small things correctly. Applying small physics principles in the right order can solve very big problems.

What advice would you give to somebody who is considering a career in laser surgery?

My education didn't start in medical school; it started by asking questions as a kid. You need a genuine love of taking on complex problems. A background in physics and math is extremely helpful. Technology in medicine is based on engineering.

Being well rounded will help you get into medical school—and get out, too. You have to be comfortable doing the science, but you also have to be comfortable dealing with people.

Highlights

KEY IDEAS

Section 1 Interference

- Light waves with the same wavelength and constant phase differences interfere with each other to produce light and dark interference patterns.
- In double-slit interference, the position of a bright fringe requires that the path difference between two interfering point sources be equal to a whole number of wavelengths.
- In double-slit interference, the position of a dark fringe requires that the path difference between two interfering point sources be equal to an odd number of half wavelengths.

Section 2 Diffraction

- Light waves form a diffraction pattern by passing around an obstacle or bending through a slit and interfering with each other.
- The position of a maximum in a pattern created by a diffraction grating depends on the separation of the slits in the grating, the order of the maximum, and the wavelength of the light.

Section 3 Lasers

- A laser is a device that transforms energy into a beam of coherent monochromatic light.

KEY TERMS

coherence (p. 527)

path difference (p. 529)

order number (p. 529)

diffraction (p. 532)

resolving power (p. 539)

laser (p. 541)

PROBLEM SOLVING

See **Appendix D: Equations** for a summary of the equations introduced in this chapter. If you need more problem-solving practice, see **Appendix I: Additional Problems.**

Variable Symbols

Quantities		Units	
λ	wavelength	m	meters
θ	angle from the center of an interference pattern	°	degrees
d	slit separation	m	meters
m	order number	(unitless)	

CHAPTER 15

Highlights

Teaching Tip

Because double-slit interference can be a difficult subject to understand, students may find it helpful to write an expository essay with diagrams, explaining how an interference pattern is created. Essays should include a discussion of diffraction as it relates to double-slit interference.

Review

ANSWERS

1. The amplitude of the resultant wave is twice the amplitude of either interfering wave, so a bright fringe forms; The amplitude of the resultant wave is zero, so a dark fringe forms.
2. by differences in brightness
3. $\lambda_{blue\ light} < \lambda_{red\ light}$, so interference fringes form at smaller angles for blue light.
4. d, m, θ
5. θ would decrease because λ is shorter in water.
6. no; because the light from the stars is not coherent
7. No interference is observed because the two waves have different wavelengths.
8. The separation of the fringes decreases because d and $\sin \theta$ are inversely proportional.
9. 630 nm
10. **a.** 589 nm
    b. 0.327°
    c. 0.436°
11. 160 μm
12. At certain angles the diffracted waves from different parts of the slit destructively interfere with each other, forming dark fringes like those observed in an interference pattern.
13. It increases as the light with longer wavelength is diffracted more.
14. Light of a particular wavelength interferes constructively at a particular angle.
15. The larger an orbiting telescope is, the more expensive it is to place in orbit. In order to

CHAPTER 15 Review

INTERFERENCE

Review Questions

1. What happens if two light waves with the same amplitude interfere constructively? What happens if they interfere destructively?

2. Interference in sound is recognized by differences in volume; how is interference in light recognized?

3. A double-slit interference experiment is performed with red light and then again with blue light. In what ways do the two interference patterns differ? (Hint: Consider the difference in wavelength for the two colors of light.)

4. What data would you need to collect to correctly calculate the wavelength of light in a double-slit interference experiment?

Conceptual Questions

5. If a double-slit experiment were performed underwater, how would the observed interference pattern be affected? (Hint: Consider how light changes in a medium with a higher index of refraction.)

6. Because of their great distance from us, stars are essentially point sources of light. If two stars were near each other in the sky, would the light from them produce an interference pattern? Explain your answer.

7. Assume that white light is provided by a single source in a double-slit experiment. Describe the interference pattern if one slit is covered with a red filter and the other slit is covered with a blue filter.

8. An interference pattern is formed by using green light and an apparatus in which the two slits can move. If the slits are moved farther apart, will the separation of the bright fringes in the pattern decrease, increase, or remain unchanged? Why?

Practice Problems

For problems 9–11, see Sample Problem A.

9. Light falls on two slits spaced 0.33 mm apart. If the angle between the first dark fringe and the central maximum is 0.055°, what is the wavelength of the light?

10. A sodium-vapor street lamp produces light that is nearly monochromatic. If the light shines on a wooden door in which there are two straight, parallel cracks, an interference pattern will form on a distant wall behind the door. The slits have a separation of 0.3096 mm, and the second-order maximum occurs at an angle of 0.218° from the central maximum. Determine the following quantities:
   a. the wavelength of the light
   b. the angle of the third-order maximum
   c. the angle of the fourth-order maximum

11. All but two gaps within a set of venetian blinds have been blocked off to create a double-slit system. These gaps are separated by a distance of 3.2 cm. Infrared radiation is then passed through the two gaps in the blinds. If the angle between the central and the second-order maxima in the interference pattern is 0.56°, what is the wavelength of the radiation?

DIFFRACTION

Review Questions

12. Why does light produce a pattern similar to an interference pattern when it passes through a single slit?

13. How does the width of the central region of a single-slit diffraction pattern change as the wavelength of the light increases?

14. Why is white light separated into a spectrum of colors when it is passed through a diffraction grating?

15. Why might orbiting telescopes be problematic for the radio portion of the electromagnetic spectrum?

Conceptual Questions

16. Monochromatic light shines through two different diffraction gratings. The second grating produces a pattern in which the first-order and second-order maxima are more widely spread apart. Use this information to tell if there are more or fewer lines per centimeter in the second grating than in the first.

17. Why is the resolving power of your eye better at night than during the day?

18. Globular clusters, such as the one shown below, are spherical groupings of stars that form a ring around the Milky Way galaxy. Because there can be millions of stars in a single cluster and because they are distant, resolving individual stars within the cluster is a challenge. Of the following conditions, which would make it easier to resolve the component stars? Which would make it more difficult?

   a. The number of stars per unit volume is half as great.
   b. The cluster is twice as far away.
   c. The cluster is observed in the ultraviolet portion instead of in the visible region of the electromagnetic spectrum.
   d. The telescope's mirror or lens is twice as wide.

Practice Problems

For problems 19–21, see Sample Problem B.

19. Light with a wavelength of 707 nm is passed through a diffraction grating with 795 slits/cm. Find the angle at which one would observe the first-order maximum.

20. If light with a wavelength of 353 nm is passed through the diffraction grating with 795 slits/cm, find the angle at which one would observe the second-order maximum.

21. By attaching a diffraction-grating spectroscope to an astronomical telescope, one can measure the spectral lines from a star and determine the star's chemical composition. Assume the grating has 3661 lines/cm.
   a. If the wavelengths of the star's light are 478.5 nm, 647.4 nm, and 696.4 nm, what are the angles at which the first-order spectral lines occur?
   b. At what angles are these lines found in the second-order spectrum?

LASERS

Review Questions

22. What properties does laser light have that are not found in the light used to light your home?

23. Laser light is commonly used to demonstrate double-slit interference. Explain why laser light is preferable to light from other sources for observing interference.

24. Give two examples in which the uniform direction of laser light is advantageous. Give two examples in which the high intensity of laser light is advantageous.

25. Laser light is often linearly polarized. How would you show that this statement is true?

MIXED REVIEW

26. The 546.1 nm line in mercury is measured at an angle of 81.0° in the third-order spectrum of a diffraction grating. Calculate the number of lines per centimeter for the grating.

27. Recall from your study of heat and entropy that the entropy of a system is a measure of that system's disorder. Why is it appropriate to describe a laser as an entropy-reducing device?

15 REVIEW

have adequate resolution, an orbiting radio telescope would have to be very large.

16. The sin θ is inversely proportional to d, which is the reciprocal of the number of lines per centimeter. The grating that spreads the pattern the most has the most lines per centimeter.
17. The pupil is larger at night, so the angle of resolution is smaller and resolving power is greater.
18. easier: a, c, d
    harder: b
19. 3.22°
20. 3.22°
21. **a.** 10.09°, 13.71°, 14.77°
    b. 20.51°, 28.30°, 30.66°
22. Laser light is coherent and monochromatic.
23. Light must be coherent for an interference pattern to form. An interference pattern is well defined with monochromatic light.
24. Answers may include distance measurements, compact disc players, and fiber-optic communications; Answers may include laser surgery and fiber-optic communications.
25. by rotating a polarizing sheet in front of the laser light—if the intensity of the transmitted light varies, the light is polarized
26. 6030 lines/cm
27. Energy (light, for example) added to the active medium's atoms is not highly ordered. This light travels in all directions, is incoherent, and is not monochromatic. The laser converts a portion of this energy into a beam of more coherent, monochromatic light.

28. 2.41×10^{-4} m
29. 432.0 nm
30. 8.000×10^{-7} m
31. 1.93×10^{-3} mm = 3 λ; a maximum

28. A double-slit interference experiment is performed using blue light from a hydrogen discharge tube (λ = 486 nm). The fifth-order bright fringe in the interference pattern is 0.578° from the central maximum. How far apart are the two slits separated?

29. A beam containing light of wavelengths λ_1 and λ_2 passes through a set of parallel slits. In the interference pattern, the fourth bright line of the λ_1 light occurs at the same position as the fifth bright line of the λ_2 light. If λ_1 is known to be 540.0 nm, what is the value of λ_2?

30. Visible light from an incandescent light bulb ranges from 400.0 nm to 700.0 nm. When this light is focused on a diffraction grating, the entire first-order spectrum is seen, but none of the second-order spectrum is seen. What is the maximum spacing between lines on this grating?

31. In an arrangement to demonstrate double-slit interference, λ = 643 nm, θ = 0.737°, and d = 0.150 mm. For light from the two slits interfering at this angle, what is the path difference both in millimeters and in terms of the number of wavelengths? Will the interference correspond to a maximum, a minimum, or an intermediate condition?

Alternative Assessment ANSWERS

1. To represent constant wavelength, the distances between lines should not exceed the lines' thickness. Students can create the same effects by overlapping drawings on computer screens.
2. One hole should produce concentric diffraction rings; two holes should produce a striped pattern. Suggested improvements will vary.
3. Students should use path difference and refraction to predict wavelengths.
4. Presentations will vary but should indicate the source material used. Young (1773–1829) was a child prodigy. Fresnel (1788–1827) was eight years old before he could read.
5. Student presentations will vary. Findings should be explained clearly.

Alternative Assessment

1. Design simulations of interference patterns. Use a computer to draw many concentric circles at regular distances to represent waves traveling from a point source. Photocopy the page onto two transparencies, and lay them on an overhead projector. Vary the distances between "source points," and observe how these variations affect interference patterns. Design transparencies with thicker lines with larger separations to explore the effect of wavelength on interference.

2. Investigate the effect of slit separation on interference patterns. Wrap a flashlight or a pen light tightly with tin foil and make pinholes in the foil. First, record the pattern you see on a screen a few inches away with one hole; then, do the same with two holes. How does the distance between the holes affect the distance between the bright parts of the pattern? Draw schematic diagrams of your observations, and compare them with the results of double-slit interference. How would you improve your equipment?

3. Soap bubbles exhibit different colors because light that is reflected from the outer layer of the soap film interferes with light that is refracted and then reflected from the inner layer of the soap film. Given a refractive index of n = 1.35 and thicknesses ranging from 600 nm to 1000 nm for a soap film, can you predict the colors of a bubble? Test your answer by making soap bubbles and observing the order in which the different colors appear. Can you tell the thickness of a soap bubble from its colors? Organize your findings into a chart, or create a computer program to predict the thicknesses of a bubble based on the wavelengths of light it appears to reflect.

4. Thomas Young's 1803 experiment provided crucial evidence for the wave nature of light, but it was met with strong opposition in England until Augustin Fresnel presented his wave theory of light to the French Academy of Sciences in 1819. Research the lives and careers of these two scientists. Create a presentation about one of them. The presentation can be in the form of a report, poster, short video, or computer presentation.

5. Research waves that surround you, including those used in commercial, medicinal, and industrial applications. Interpret how the waves' characteristics and behaviors make them useful. For example, investigate what kinds of waves are used in medical procedures such as MRI and ultrasound. What are their wavelengths? Research how lasers are used in medicine. How are they used in industry? Prepare a poster or chart describing your findings, and present it to the class.

Graphing Calculator Practice

Double-Slit Experiment

One of the classic experiments that demonstrate the wave nature of light is the double-slit experiment. In this experiment, light from a single source is passed through a narrow slit and then through two narrow parallel slits. When the light appears on a viewing screen behind the slits, you see a pattern of alternating bright and dark fringes corresponding to constructive and destructive interference of the light.

As you studied earlier in the chapter, the bright fringes are described by the following equation.

$$d \sin \theta = \pm m\lambda$$

In this equation, d is the slit separation, θ is the fringe angle, m is the order number, and λ is the wavelength of the incident wave. Typically, only the first few fringes ($m = 0, 1, 2, 3$) are bright enough to see.

In this graphing calculator activity, you will calculate a table of fringe angles. By analyzing this table, you will gain a better understanding of the relationship between fringe angles, wavelength, and slit separation.

Visit go.hrw.com and enter the keyword **HF6INFX** to find this graphing calculator activity. Refer to **Appendix B** for instructions on downloading the program for this activity.

extension

Graphing Calculator Practice

Visit go.hrw.com for answers to this Graphing Calculator activity.

Keyword HF6INFXT

Standardized Test Prep

ANSWERS

1. B
2. H
3. C
4. G
5. C
6. H
7. B

Standardized Test Prep

MULTIPLE CHOICE

1. In the equations for interference, what does the term d represent?

A. the distance from the midpoint between the two slits to the viewing screen
B. the distance between the two slits through which a light wave passes
C. the distance between two bright interference fringes
D. the distance between two dark interference fringes

2. Which of the following must be true for two waves with identical amplitudes and wavelengths to undergo complete destructive interference?

F. The waves must be in phase at all times.
G. The waves must be 90° out of phase at all times.
H. The waves must be 180° out of phase at all times.
J. The waves must be 270° out of phase at all times.

3. Which equation correctly describes the condition for observing the third dark fringe in an interference pattern?

A. $d \sin \theta = \lambda/2$
B. $d \sin \theta = 3\lambda/2$
C. $d \sin \theta = 5\lambda/2$
D. $d \sin \theta = 3\lambda$

4. Why is the diffraction of sound easier to observe than the diffraction of visible light?

F. Sound waves are easier to detect than visible light waves.
G. Sound waves have longer wavelengths than visible light waves and so bend more around barriers.
H. Sound waves are longitudinal waves, which diffract more than transverse waves.
J. Sound waves have greater amplitude than visible light waves.

5. Monochromatic infrared waves with a wavelength of 750 nm pass through two narrow slits. If the slits are 25 μm apart, at what angle will the fourth-order bright fringe appear on a viewing screen?

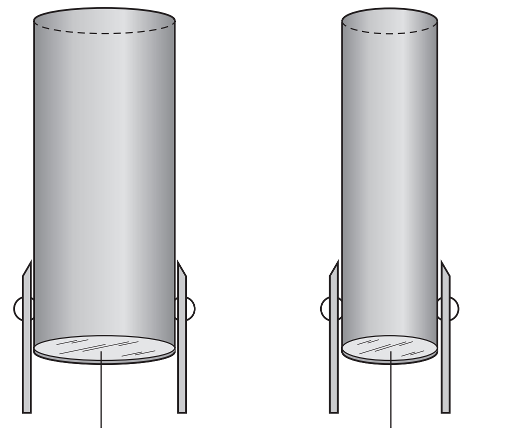
A. 4.3°
B. 6.0°
C. 6.9°
D. 7.8°

6. Monochromatic light with a wavelength of 640 nm passes through a diffraction grating that has 5.0×10^4 lines/m. A bright line on a screen appears at an angle of 11.1° from the central bright fringe. What is the order of this bright line?

F. $m = 2$
G. $m = 4$
H. $m = 6$
J. $m = 8$

7. For observing the same object, how many times better is the resolution of the telescope shown on the left in the figure below than that of the telescope shown on the right?

A. 4
B. 2
C. $\frac{1}{2}$
D. $\frac{1}{4}$



Area of mirror = 80 m^2 Area of mirror = 20 m^2

8. What steps should you employ to design a telescope with a high degree of resolution?
   F. Widen the aperture, or design the telescope to detect light of short wavelength.
   G. Narrow the aperture, or design the telescope to detect light of short wavelength.
   H. Widen the aperture, or design the telescope to detect light of long wavelength.
   J. Narrow the aperture, or design the telescope to detect light of long wavelength.

9. What is the property of a laser called that causes coherent light to be emitted?
   A. different intensities
   B. light amplification
   C. monochromaticity
   D. stimulated emission

10. Which of the following is *not* an essential component of a laser?
   F. a partially transparent mirror
   G. a fully reflecting mirror
   H. a converging lens
   J. an active medium

SHORT RESPONSE

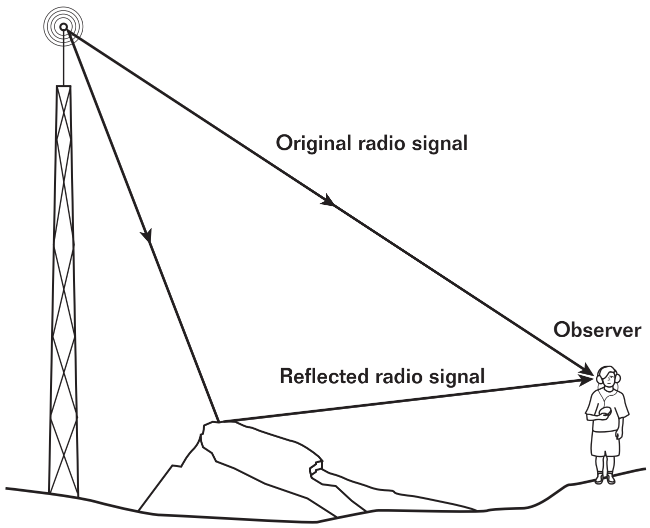
11. Why is laser light useful for the purposes of making astronomical measurements and surveying?

12. A diffraction grating used in a spectrometer causes the third-order maximum of blue light with a wavelength of 490 nm to form at an angle of 6.33° from the central maximum ($m = 0$). What is the ruling of the grating in lines/cm?

13. Telescopes that orbit Earth provide better images of distant objects because orbiting telescopes are more able to operate near their theoretical resolution than telescopes on Earth. The orbiting telescopes needed to provide high resolution in the visible part of the spectrum are much larger than the orbiting telescopes that provide similar images in the ultraviolet and X-ray portion of the spectrum. Explain why the sizes must vary.

EXTENDED RESPONSE

14. Radio signals often reflect from objects and recombine at a distance. Suppose you are moving in a direction perpendicular to a radio signal source and its reflected signal. How would interference between these two signals sound on a radio receiver?



Base your answers to questions 15–17 on the information below. In each problem, show all of your work.

A double-slit apparatus for demonstrating interference is constructed so that the slits are separated by 15.0 μm. A first-order fringe for constructive interference appears at an angle of 2.25° from the zeroth-order (central) fringe.

15. What is the wavelength of the light?

16. At what angle would the third-order ($m = 3$) bright fringe appear?

17. At what angle would the third-order ($m = 3$) dark fringe appear?

Test TIP Be sure that angles in all calculations involving trigonometric functions are computed in the proper units (degrees or radians).

8. F
9. D
10. H
11. The beam does not spread out much or lose intensity over long distances.
12. 7.5×10^4 lines/m = 750 lines/cm
13. The resolving power of a telescope depends on the ratio of the wavelength to the diameter of the aperture. Telescopes using longer wavelength radiation (visible light) must be larger than those using shorter wavelengths (ultraviolet, X ray) to achieve the same resolving power.
14. The interference pattern for radio signals would "appear" on a radio receiver as an alternating increase in signal intensity followed by a loss of intensity (heard as static or "white noise").
15. 589 nm
16. 6.77°
17. 7.90°

Lab Planning

Beginning on page T34 are preparation notes and teaching tips to assist you in planning.

Blank data tables (as well as some sample data) appear on the **One-Stop Planner.**

No Books in the Lab?

See the ***Datasheets for In-Text Labs*** workbook for a reproducible master copy of this experiment.

Safety Caution

Make sure all students know the proper procedure for cleaning up broken glass. Remind students not to attempt to remove broken bulbs from sockets.

Tips and Tricks

- Before the lab, demonstrate diffraction using an excited gas source. Set up the optical bench as described in step 3 of the lab, and place the light source about 5 cm away from the slit. Adjust the grating and the slit scale distance and angle so a full first-order and part of a second-order spectrum appear centered about the slit. Show students how to recognize the images and how to bend paper clips to form riders for marking each similar first-order image and each similar second-order image.

Skills Practice Lab Diffraction

OBJECTIVES

- **Discover** wavelengths of diffracted light.

MATERIALS LIST

- **bent paper-clip riders for meterstick**
- **black cardboard**
- **cellophane tape**
- **diffraction grating**
- **grating holder and support**
- **incandescent light source and power supply**
- **meterstick and 2 supports**
- **metric scale and slit**

In this experiment, you will pass white light through a diffraction grating and make measurements to determine wavelengths of the light's components.

SAFETY

- **Avoid looking directly at a light source. Looking directly at a light source can cause permanent eye damage. Put on goggles.**
- **Use a hot mitt to handle resistors, light sources, and other equipment that may be hot. Allow all equipment to cool before storing it.**
- **If a bulb breaks, notify your teacher immediately. Do not remove broken bulbs from sockets.**
- **Never put broken glass or ceramics in a regular waste container. Use a dustpan, brush, and heavy gloves to carefully pick up broken pieces and dispose of them in a container specifically provided for this purpose.**

PROCEDURE

Preparation

1. Read the entire lab, and plan the steps you will take.
2. If you are not using a datasheet provided by your teacher, prepare a data table in your lab notebook with six columns and four rows. In the first row, label the columns *Light Source, Image Color, Order, Image 1 (m), Image 2 (m),* and *Slit (m).* In the first column, label the second through fourth rows *White.* Above or below the data table, prepare a space to record the slit spacing, *d,* of the grating.

Wavelengths of White Light

3. Set up the optical bench as shown in **Figure 1.** Mount the scale and slit on one end of the optical bench, and place a piece of tape over the slit. Place a cardboard shield around the light source to direct all the light through the slit. Illuminate the slit with white light. Mount the grating near the opposite end of the optical bench.
4. Adjust the apparatus so that the white-light source is centered on the slit and the slit scale is perpendicular to the optical bench. Tape the optical bench and the white-light source securely in place.

5. With your eye close to the grating, observe the first-order spectra. Move the grating forward or backward as required so that the entire spectrum appears on each side of the scale. Place a bent paper-clip rider on the scale at the point in each first-order spectrum where the yellow light is the purest. Adjust the grating and slit scale by rotating the grating around its vertical axis so that the two yellow points end up equidistant from the source slit. Reposition the riders if necessary.

6. Use the scale to measure the distance from the slit to each rider to the nearest millimeter. Record these distances in your data table as *Image 1* and *Image 2*. Also measure the distance from the slit to the grating. Record this distance in your data table as the *Slit (m)*. Record the order number and the image color.

7. Next, adjust the grating and slit to find the clearest first-order continuous spectrum. Measure and record the distance from the slit to the grating. Place a rider on the scale at the point in each first-order spectrum where you see the extreme end of the violet spectrum. Measure and record the distance from the slit to each rider.

8. Repeat step 7 for the extreme red end of the spectrum. Record all data.

9. Clean up your work area. Put equipment away safely so that it is ready to be used again. Recycle or dispose of used materials as directed by your teacher.

ANALYSIS

1. **Organizing Data** Use your data for each trial.

   a. For each trial, find the average image position.

   b. Use the average image position and the distance from the slit to the grating to find the distance from the grating to the image for each trial. (Hint: Use the Pythagorean theorem.)

   c. To find sin θ for each trial, divide the average image position by the distance found in (b).

CONCLUSIONS

2. **Drawing Conclusions** For each trial, find the wavelength of the light using the equation $\lambda = \frac{d\,(\sin\theta)}{m}$, where λ is the wavelength of light (in meters, m), d is the diffraction-grating spacing (1/[number of lines/m]), and m is the order number of the spectrum containing the image.

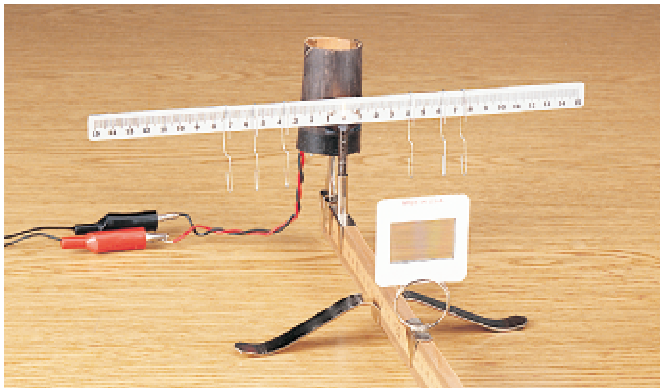


Figure 1
Step 3: Use the cardboard to make a shield around the light source. Make sure the light is directed through the slit.
Step 4: From above, the slit scale should form right angles with the meterstick. Measurements can be strongly affected if the equipment is moved even slightly during the procedure.
Step 5: Place a bent paper-clip rider to mark the position of the images on the scale.

CHAPTER 15 LAB

✓ Checkpoints

Step 4: Make sure the apparatus is firmly attached to the table. Large errors can occur if the equipment is moved even slightly during the procedure.

Step 5: Students may need help finding the correct position of the grating. Students should be able to demonstrate that they have found the point in the spectrum where the color is purest.

Step 6: Students should be able to demonstrate how they used the scale to measure the distances.

ANSWERS

Analysis

1. a. yellow: 0.096 m
violet: 0.067 m
red: 0.118 m

b. Student answers will vary. For sample data, values range from 0.302 m to 0.318 m.

c. For sample data, values range from 0.22 to 0.37.

Conclusions

2. yellow: $\lambda = 5.68 \times 10^{-7}$ m
violet: $\lambda = 4.04 \times 10^{-7}$ m
red: $\lambda = 6.80 \times 10^{-7}$ m