33

Diffraction

Seeing Around the Corner

Purpose

To investigate the diffraction and the interference of light.

Required Equipment and Supplies

helium-neon laser
demonstration slits (Sargent-Welch Company)
lens
4 x 6 card with 1-cm hole in the center
adhesive metal tape (duct tape)
large white card to use as a screen
meterstick or optical bench
modeling clay or lens holders
compact disc

Discussion

We know that light can be bent from its ordinary straight line path by reflection and refraction. We will see here that there is another way light bends. Any bending of light by means other than reflection and refraction is called *diffraction*.

When light passes through an opening that is large compared to the wavelength of light, it casts a shadow. We see a rather sharp boundary between the light and dark area of the shadow. But if light passes through a thin razor slit in a piece of opaque cardboard, we see that the light diffracts (Figure 33.1). The sharp boundary between the light and the dark area disappears, and the light spreads out like a fan to produce a bright area that fades into darkness without sharp edges. The light is diffracted.

After investigating some interesting properties of diffraction, you will estimate the thickness of a hair and the diameter of a red blood cell.

Part A: Diffraction

Procedure

Step 1. The laser emits a beam of light whose diameter is about 1 mm. You may enlarge the diameter of the laser beam by passing it through a lens. Place the lens at one end of your optical bench and a screen at the

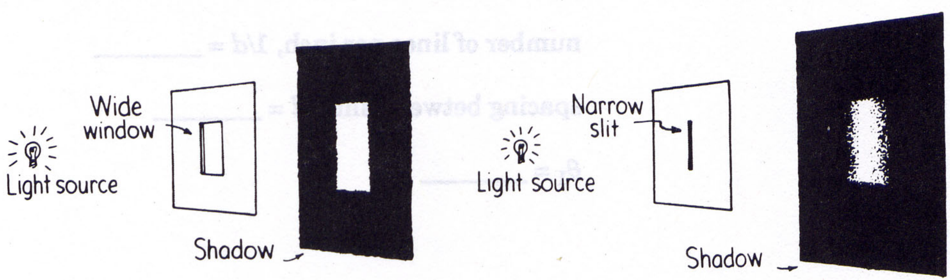

Figure 33.1

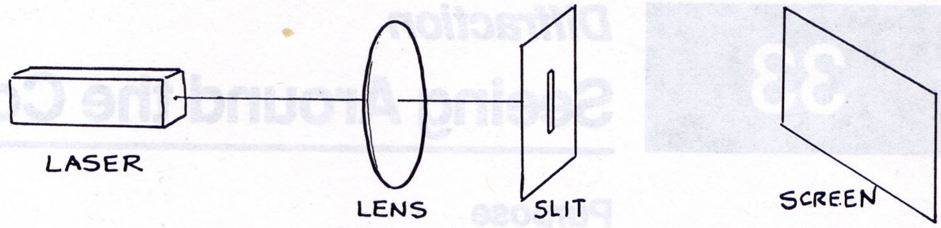

Figure 33.2

other end. Place the single slit near the lens and illuminate the slit with the enlarged laser beam as shown in Figure 33.2. Observe the diffraction pattern as you vary the slit width.

1. What happens to the diffraction pattern as the slit width becomes smaller? What diffraction pattern would you expect if the slit were reduced to a small square? Try it and see by reducing the the aperture to a small square and then observing the diffraction pattern. Sketch the observed pattern below.

Step 2. Replace the single slit with a double slit and observe the diffraction pattern. Observe the diffraction pattern as you vary the slit width. Sketch the observed pattern below.

2. How does the diffraction pattern vary with the distance between the two slits?

3. How do the diffraction patterns formed by a single slit compare to the diffraction pattern of a double slit?

Step 3. Replace the double slit with a grating and observe the diffraction pattern. Your instructor will provide you with the spacing between adjacent slits, *d*, which is usually specified by the number of lines per inch, $1/d$. Measure two distances such that the angle θ_1 (angular position of the first-order maximum, $n = 1$) can be calculated.

number of lines per inch, $1/d$ = ________

spacing between slits, d = ________

θ_1 = ________

Step 4. Using the equation $n\lambda = d\sin\theta$, calculate the wavelength, λ, of the laser.

λ = ________

Analysis

4. Helium-neon lasers generally emit red light with a wavelength of 632.8 nm (632.8×10^{-9} m). How does your calculated value for λ compare with 632.8 nm? Calculate the percentage discrepancy.

percentage discrepancy = ________

5. Assuming the wavelength of the laser light quoted above is correct, what sources of error would account for any discrepancies?

Part B: Resolution

Procedure

Step 5. Stick a piece of adhesive metal tape across the 1-cm hole in the card. Mount the card, screen and lens as shown in Figure 33.3. Twirl a pin to make a good circular hole in the tape at the center of the laser spot. Observe the diffraction pattern due to the circular hole.

6. How can you tell from the observed diffraction pattern whether or not the hole is truly circular?

Step 6. Twirl a second hole about 1 or 2 mm from the first hole. Position the laser so that both holes are illuminated. Observe the diffraction patterns by initially holding the screen a few centimeters from the holes and then slowly moving the screen to a few meters away from the holes.

At first, you should have no difficulty observing two well resolved spots of light on the screen. As the screen is moved away each spot takes on the character of a diffraction pattern and eventually the two patterns merge into one. Resolution of the spots has been washed out by diffraction.

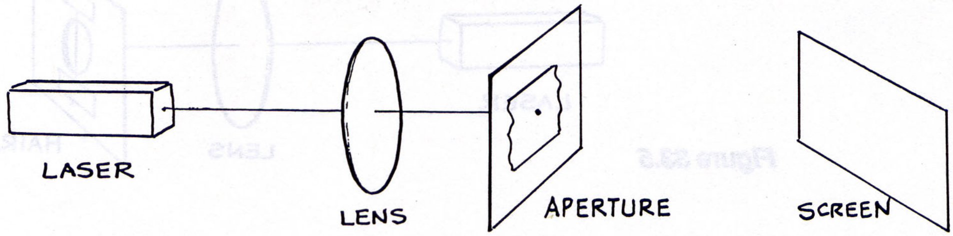

Figure 33.3

The Rayleigh criterion for resolution stipulates that two images are just resolved when the center of one pattern falls on the first dark band of the other. Is this what you observed? Sketch the diffraction pattern you observe when the Rayleigh criterion is satisfied.

Part C: Diffraction Measurement Techniques

Discussion

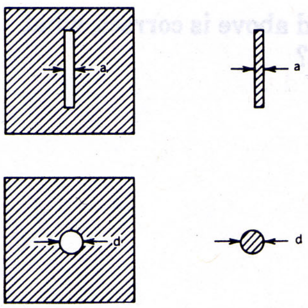

Figure 33.4

Babinet's principle states that the diffraction patterns produced by two complementary screens are the same. The term complementary here signifies that the opaque spaces in one screen are replaced by transparent spaces in the other, and vice versa. For example, a single slit and a thin wire or hair of diameter equal to the slit width are complementary screens. Likewise, a circular hole and a disk of the same diameter are complementary screens. These two examples are shown in Figure 33.4. This principle can be useful when trying to measure small distances. We can use Babinet's principle to state that a human hair and a single slit are complementary screens.

Estimating the Thickness of a Hair

Step 7. Remove the adhesive metal tape from the card having a 1-cm hole. Stretch a hair across the hole and tape it on each side. Mount the card and a screen on the meterstick and illuminate the hair with the laser as shown in Figure 33.5. The lens, used to enlarge the beam diameter, is not needed. From the geometry of your experiment, determine the angular position, θ_2, of the second minimum ($n = 2$).

θ_2 = ________

Step 8. Calculate the hair thickness using the equation $d \sin\theta_2 = n\lambda$, where d is the thickness of the hair, θ_2 is the angular position of the second minimum, and n is the diffraction order.

d = ________

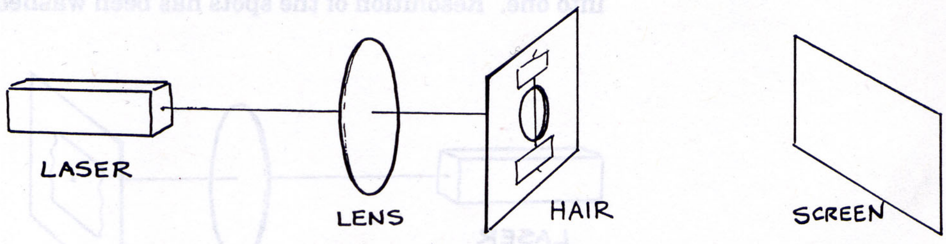

Figure 33.5

Table 33.1

FRINGE	1st	2nd	3rd	4th	5th
n	1.22	2.23	3.24	4.24	5.24

Estimating the Diameter of a Red Blood Cell

The equation for the angular position of the minima for a circular opening of diameter d has the same form as that for the linear diffraction pattern produced by a single slit:

$$n\lambda = d \sin\theta$$

where n is a non-integer constant which has the value 1.22 for the first dark fringe (with successive values as indicated in Table 33.1) and λ is the wavelength of the diffracted light. Although this equation is similar in form to other diffraction equations, the derivation is beyond the scope of this course.

The first dark ring occurs at an angular displacement given by

$$\sin\theta_1 = 1.22\frac{\lambda}{d}$$

A diagram of the angle, θ, is shown in Figure 33.6.

Step 9. A red blood cell and a circular hole are complementary screens. Mount a glass slide which has a blood smear and a screen on the meterstick with clay or appropriate holders. Place the screen about 6 or 8 centimeters from the slide. Adjust the lateral position of the laser until a circular diffraction pattern is observed on the screen. Shining the laser beam on the edge of the blood smear (where the smear is thinner) will produce the best diffraction pattern.

Note: The red blood cells are easily damaged when making a blood smear. For best results, *gently* smear a drop of blood on a slide with another slide so as not to damage the cells.

Determine the angular position, θ_1, of the first dark ring from the geometry of your experiment.

$\theta_1 =$ ________

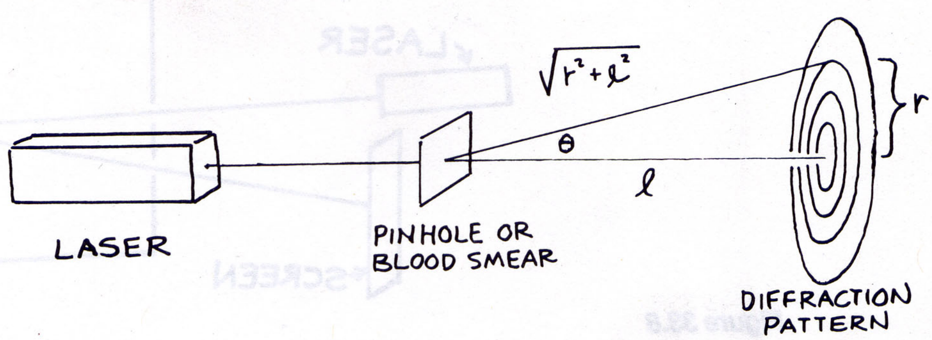

Figure 33.6

Calculate the diameter of a red blood cell.

$d =$ ________

The diameter of a red blood cell depends on its age (its mean lifetime is about 128 days) but an average value is 7.5 x 10^{-6} m. How does your calculated value for the red blood cell compare with the average value?

Going Further

Estimating the Separation Distance on a Compact Disc

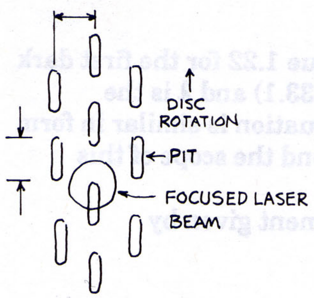

Figure 33.7

The bottom of a compact disc is a highly reflective surface containing a spiral of "pits." If stretched out, this spiral would be about 5 km long! The pits are arranged in a fashion similar to that shown in Figure 33.7. Each pit is 0.5 µm (0.5 x 10^{-6} m) wide and is separated from each adjoining row by a distance of 1.6 µm—an industrial standard. The spiral of pits behave much the same as a diffraction grating. When a laser beam is reflected off the bottom side of the disc, a familiar diffraction pattern is formed. If the angle of incidence of the laser beam is small, the distance between the rows of pits, *d*, can be estimated by:

$$d \sin \theta = n\lambda$$

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

where n is the diffraction order, and θ is the angular position of the nth maximum.

Step 10. Arrange a disc, laser, and screen as shown in Figure 33.8. The laser should be about one meter from the disc. Direct the laser beam such that it strikes the compact disc approximately half way up, as shown in Figure 33.9. This arrangement will give you a horizontal diffraction

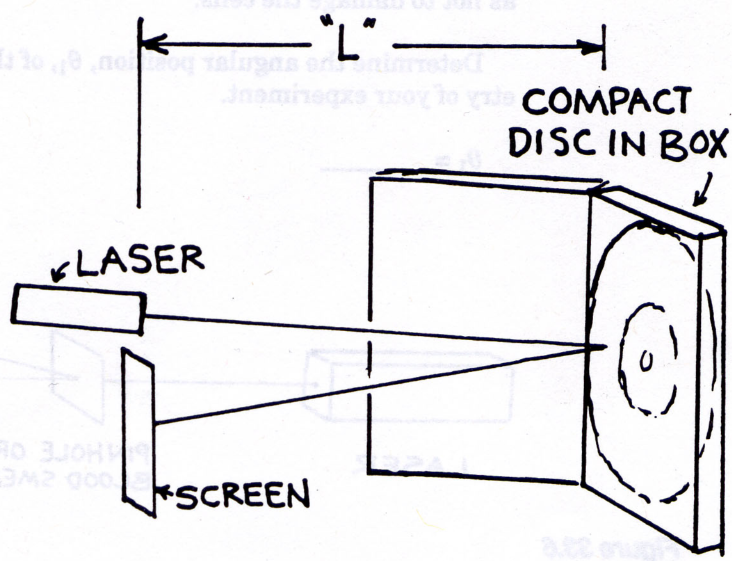

Figure 33.8

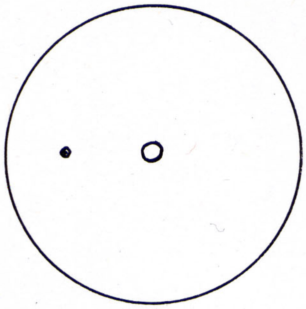

Figure 33.9

patttern on the screen with a central bright spot followed by the first-order maximum, etc. Determine the angular position, θ_1, of the first-order maximum, from the geometry of your experiment.

θ_1 = ________

Assuming the red light of your laser beam has a wavelength of 632.8 nm, calculate the distance between the rows of pits.

d = ________

How does your value compare with 1.6 μm? Compute the percentage difference.

percentage difference = ________