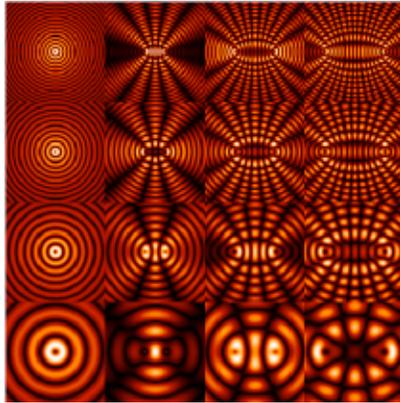


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UNIT 31: INTERFERENCE AND DIFFRACTION



Interference of two circular waves, snapshots of absolute value of (real, scalar) wave field for different wave lengths and distances of point sources. (Wikimedia Commons)

OBJECTIVES

1. Understand the creation of double-slit interference and single-slit diffraction patterns.
2. Measure slit separation using double-slit interference of He-Ne laser light.
3. Compare single slit diffraction patterns to double-slit patterns.
4. Examine some 2-D diffraction patterns.
5. Construct and calibrate a portable diffraction-grating spectrometer and use it to examine the spectra of several light sources.

OVERVIEW

In 1802 the supremacy of the particle theory of light was shattered by a simple interference experiment performed by Thomas Young. He let light from a pinhole fall on two slits in an opaque screen. If the slits were close enough to each other then the emerging light formed alternate bright and dark fringes on a screen. Newton's particle theory of light could not account for these bands.

In this unit we are going to explore the wave phenomena of interference and diffraction. The fringes that Young produced in his famous experiment are the result of what is known as double-slit interference. Interference occurs when two or more waves occupy the same space at the same time. The interfering waves combine either constructively or destructively depending on their relative phases. As can be seen in Figure 31.1 below, when two waves are completely in phase they *constructively* interfere and produce a wave with an increased amplitude. Likewise when two waves are out of phase by half a cycle they *destructively* interfere and produce a wave with a decreased amplitude, even no amplitude if the original two waves are of equal amplitude.

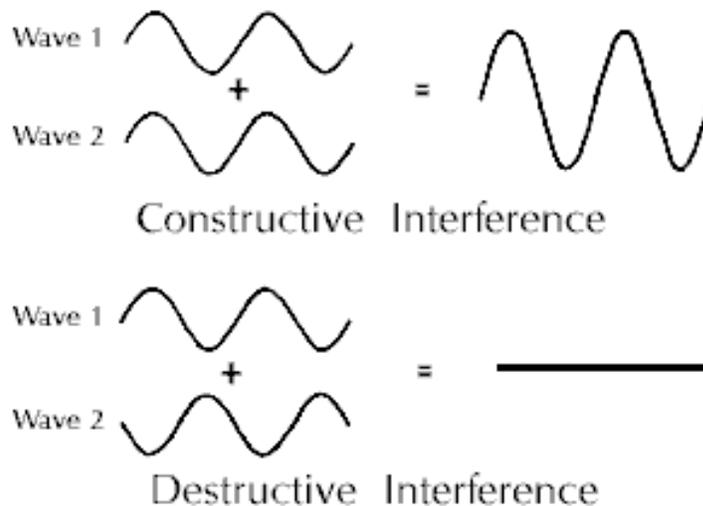


Figure 31.1: Constructive and destructive interference.

SESSION ONE: INTERFERENCE

We are going to begin by examining what happens when two circular waves interfere. Circular waves are the two dimensional equivalent of the three dimensional spherical waves produced by point sources. You get circular waves from point disturbances on the surface of still water. In the diagram of a circular wave shown in Figure 31.2 shown below, the dark lines represent crests and the dotted lines represent troughs. This is how the wave would appear at one instant in time.

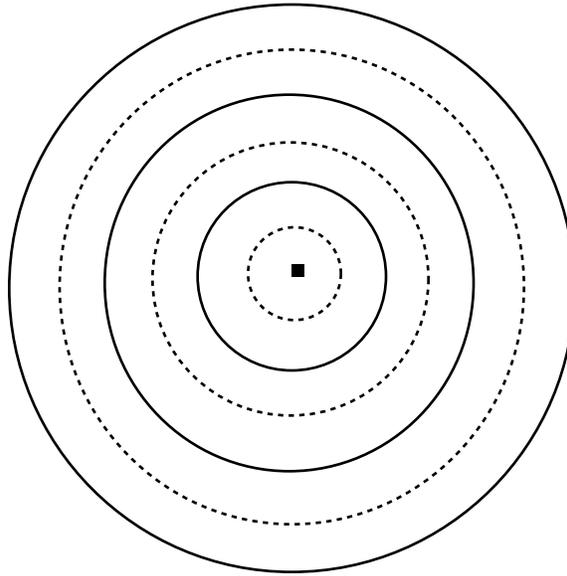


Figure 31.2: A circular wave.

Activity 31-1: Two source interference

(a) On Figure 31.2, indicate how long a wavelength is. How would the image of the wave differ if you looked at it one half period later in time?

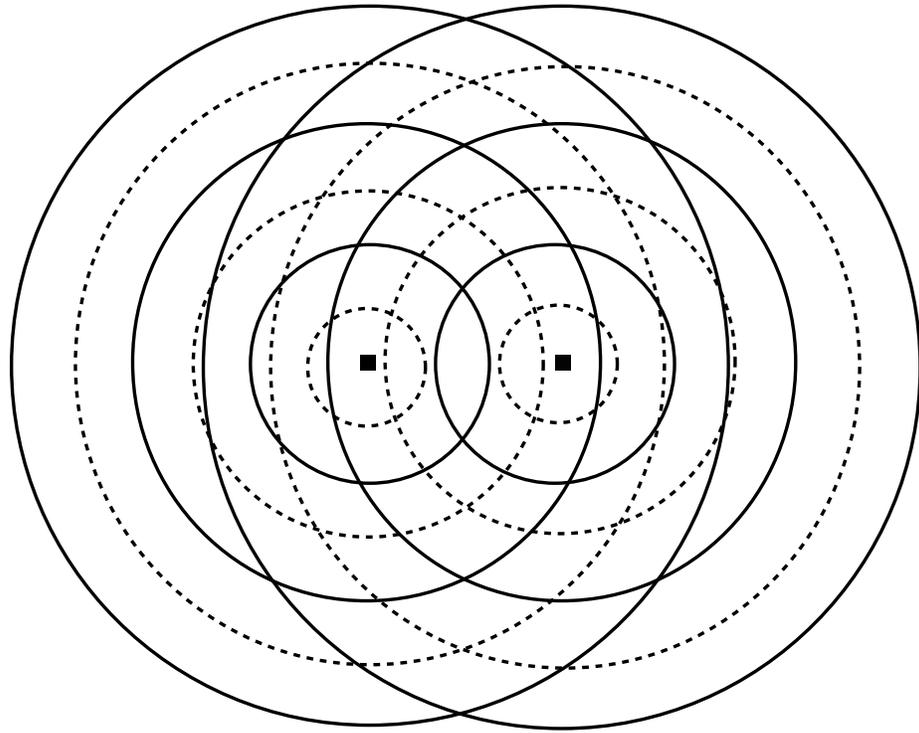


Figure 31.3: Two circular waves interfering.

(b) Now examine Figure 31.3 which shows two circular waves interfering. How do the frequencies of the two wave sources compare if they're travelling in the same medium and so have the same wave speed?

(c) Are the two sources in this diagram in phase or out of phase with each other? Explain how you can tell.

(d) What is the approximate source separation in terms of the wavelength?

(e) Describe what happens when:

i) a crest meets a crest

ii) a crest meets a trough

iii) a trough meets a trough

(f) On Figure 31.3, indicate with three different symbols several places where i, ii, and iii from part e) occur. What patterns do you notice? Try to draw straight lines connecting the same consecutive symbols. Describe the patterns you see in words below.

(g) The diagram we have been using represents one instant in time. Consider a point in your diagram where a crest meets a crest. How would the disturbance at this location (if this were a wave on the surface of water for example) change with time? How would it look one-half period later?

(h) Now examine a point where a crest meets a trough . How would the disturbance at this location change with time?

Double-slit Interference

You have just examined the interference pattern of two point-like wave sources. When light is shown onto two slits as occurred in Young's experiment, the slits act like point-like wave sources and a similar pattern emerges.

Huygens' wave model states that each point on a wave front can be considered the source of a spherical wave. The superposition of all the little spherical waves produced at a wave front add up to continue propagating the wave forward. Placing a barrier with two slits in the path of a wave front will allow only the waves passing through the slits to continue forward. Thus two cylindrical waves emerge from the slits which can interfere with each other much like our two circular waves. If a screen is placed at some distance from the two slits then a pattern of bright and dark fringes can be seen on it corresponding to locations where constructive and destructive interference occur. This is illustrated in Figure 31.4 below.

If a location on the screen is an integral number of wavelengths from both slits as seen in Figure 31.5 then the interference is constructive and a bright line results. When the screen is much farther from the slits than the slits are apart the Fraunhofer approximation holds and bright fringes occur angles defined by the following relation:

$$d \sin \theta = m\lambda, m = 0, 1, 2, \dots \quad (31.1)$$

where m is an integer, d is the distance between slits, λ is the wavelength and θ is the angle between the direction of incidence, which is assumed normal to the slit plane, and the fringe on the screen. Dark fringes occur when

$$d \sin \theta = (m + 1/2)\lambda, m = 0, 1, 2, \dots \quad (31.2)$$

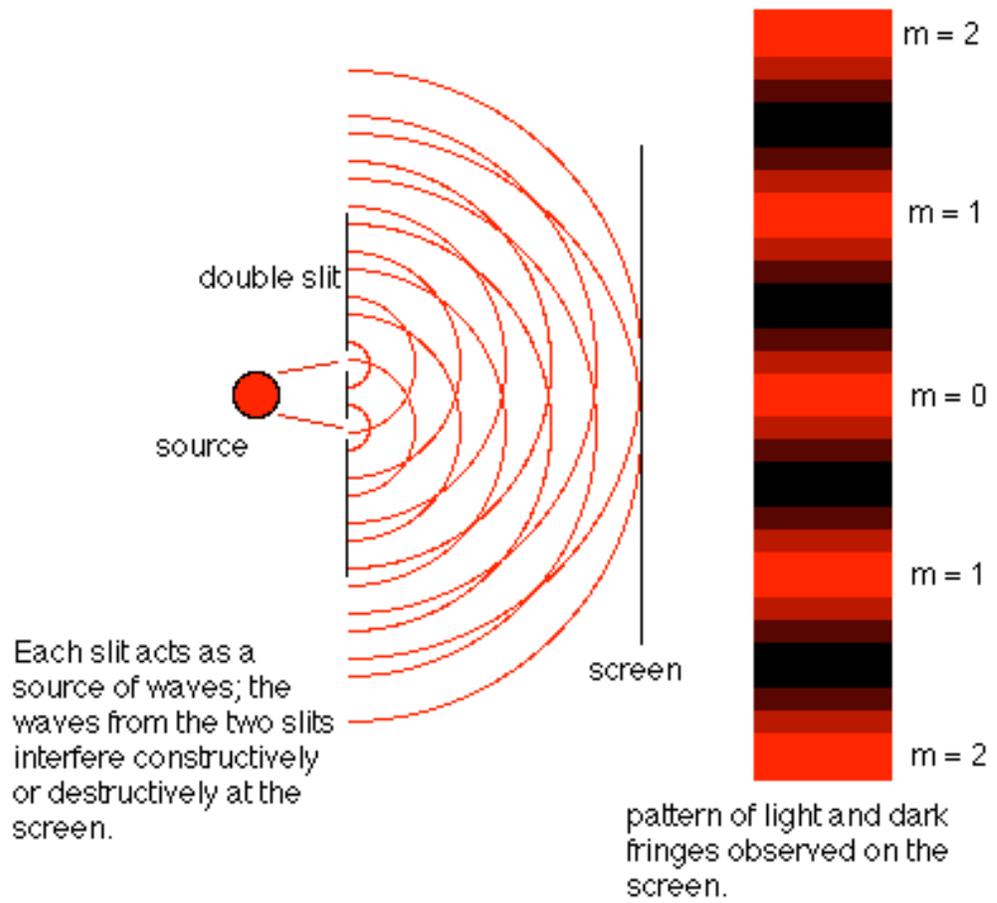


Figure 31.4: The creation of a double-slit interference pattern.

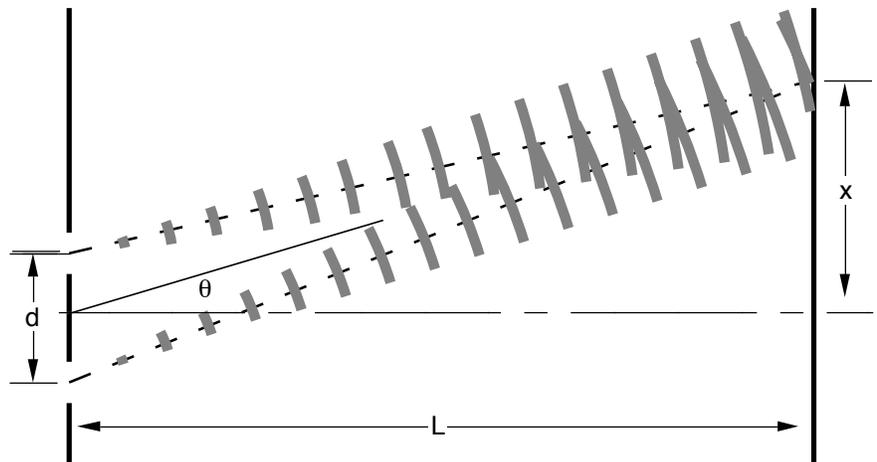


Figure 31.5: Double slit interference forms bright fringes where waves fall on the screen in phase. $m = 1$ is shown here, which means the path lengths differ by one wavelength.

As can be seen in Figure 31.5, the angle θ of a particular fringe can be determined by measuring x and L and using the fact that $\tan \theta = x/L$. For small values of θ like we often have in interference experiments, one can use the small angle approximation which states that: $\sin \theta \sim \tan \theta \sim \theta$ (with θ in radians). (For a full derivation of these formulas see your textbook.)

Complications disturb this ideal situation. Because in the real world the slits cannot be infinitesimally small, the brightness of the fringes decreases as θ increases, and becomes invisibly dim at larger angles. This arises because a single-slit diffraction pattern is superimposed on the ideal double-slit pattern. The finite width of each slit allows light passing through to interfere with itself causing complete cancellation at definite angles. If light from each slit cancels itself out, then there is none left to produce a bright fringe. Later in this unit you will learn about diffraction and compare the patterns created by single slits to those made by double slits having the same width .

For the following activities you will need:

- Optics Kit
- He-Ne Laser with mount
- Post-it notes, 3"×5"

Activity 31-2: Double Slit Interference

(a) Mount the He-Ne laser on the end of the optical bench. Put the diffraction plate on the component holder with aperture D centred. Turn on the laser and shine the light directly onto the double slit. Don't hit the clear window above the slit. Make a screen at the far end of the optical bench by pasting Post-it notes just below the rulings on the diffraction scale and mounting it on the front of the ray table base (See Figure 31.6.). The scale is made to be illuminated from the back so that you can see the diffraction pattern in the dark while measuring fringe positions. Count the total number of bright fringes you can see and record this number below. (**Hint:** You may wish to use the 150 mm lens as a magnifying glass as the pattern is quite small. Slide the scale back as far as you can to maximize the pattern spacing.)

(b) The fringe spacing x can be determined by measuring the total length of the fringe pattern you can see, X , and dividing it by the number of fringes N : $x = X/N$. Show your calculation of x below.

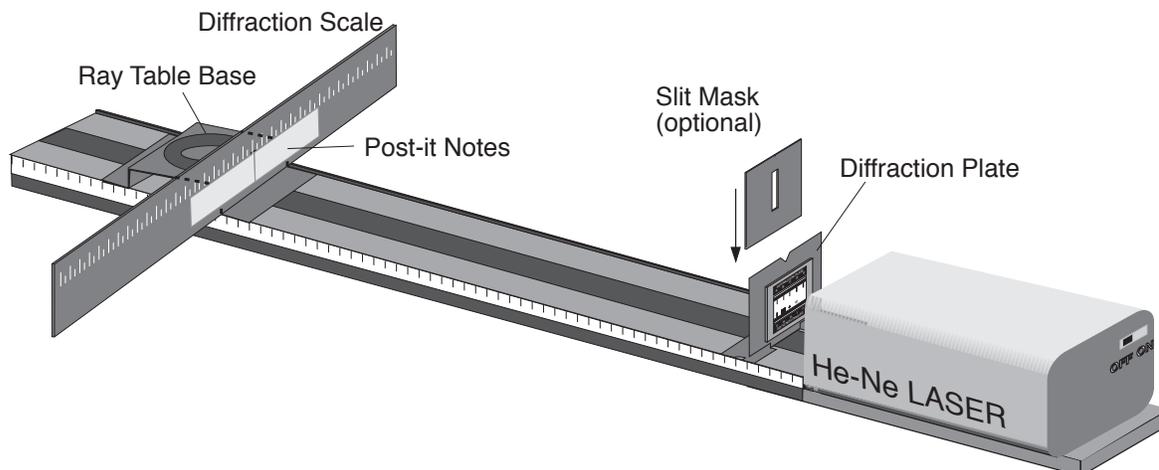


Figure 31.6: Set-up to study interference using the He-Ne laser.

(c) Measure and record the distance between the slits and the screen L .

(d) From your values for x and L , determine the angle θ where the first order ($m = 1$) bright fringe occurs.

(e) Use Equ. 31.1 to determine the slit separation d . (The wavelength of the He-Ne laser light is 632.8 nm.) Record your result below. How does your d value agree with the “true” value provided by your instructor? Calculate a percent difference between the two values.

(f) Repeat steps (a)-(e) to determine the slit separation of aperture E. Record your data below and show all of your work in the space provided.

SESSION TWO: DIFFRACTION

Diffraction

Diffraction occurs when a wave front encounters a slit whose width is similar in size to the wavelength. After having passed through the slit, the wave front spreads out into the region on the other side as illustrated in Figure 31.7. The amount of spreading is dependent upon the width of the slit.

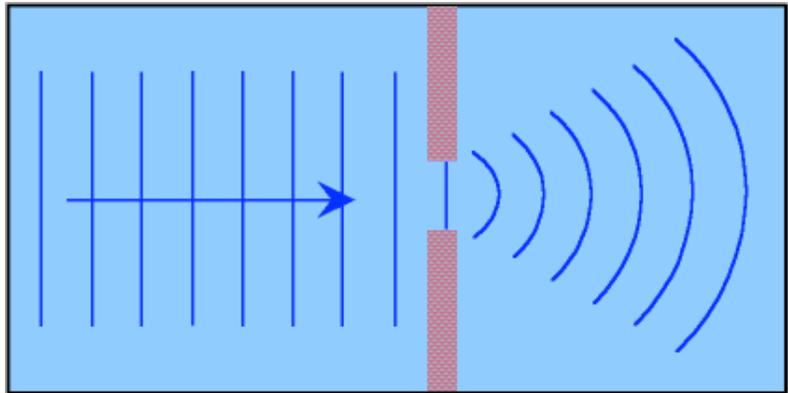


Figure 31.7: Diffraction of a wave front.

When a screen is placed some distance from the slit, a pattern of bright and dark fringes with an intense central maximum can be seen as shown in Figure 31.8.

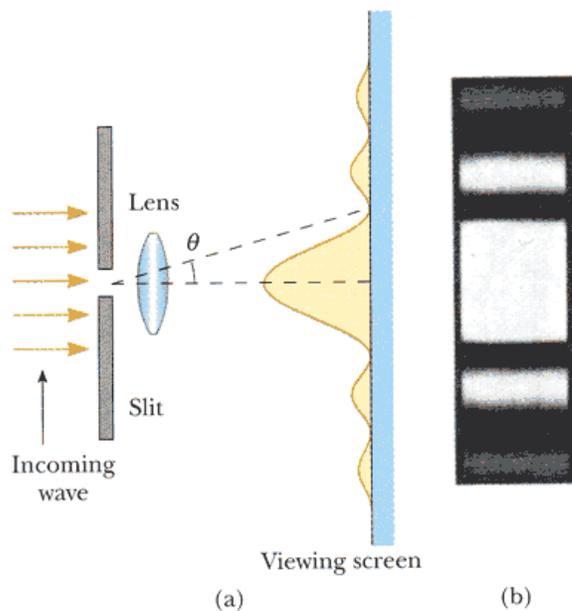


Figure 31.8: (a) Single-slit diffraction and (b) the corresponding pattern seen on a viewing screen.

This pattern results from interference between wavelets travelling through different parts of the slit. The central bright fringe is easy to explain because the Huygens' wavelets from all points in the slit travel about the same distance to reach the centre of the pattern and thus are in phase there. To find the locations of the dark fringes one can pair up all of the rays coming from the slit and find out what conditions cause the wavelets in each pair to destructively interfere. This analysis has been done in your textbook. Therefore we will just present the results here.

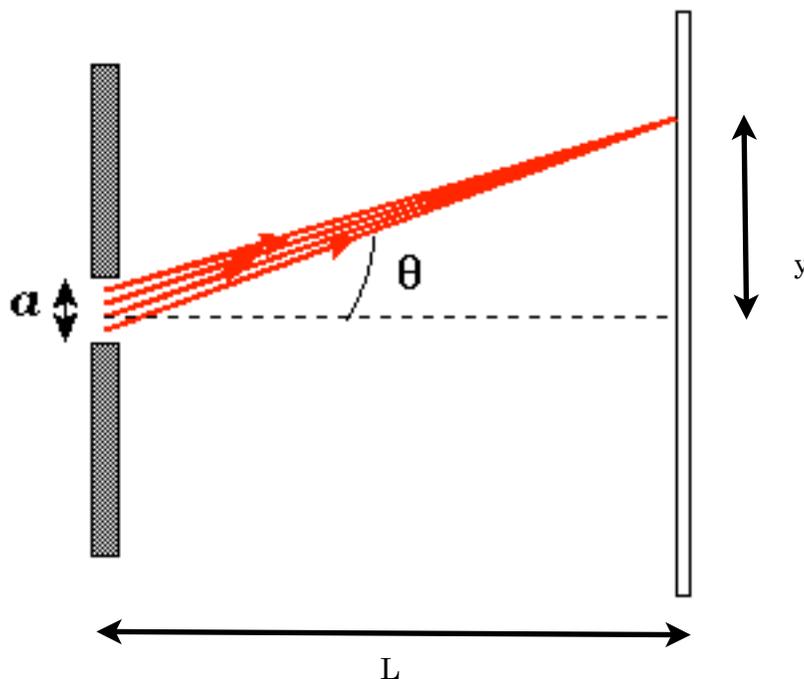


Figure 31.9: Locating a minimum in a single-slit diffraction pattern.

The dark fringes or minima occur when the following condition is met:

$$a \sin \theta = m \lambda, \quad m = 1, 2, 3, \dots \quad (31.3)$$

where a is the width of the slit, θ is the angle at which the dark fringe occurs, m is the order of the fringe and λ is the wavelength of the light. This physically corresponds to the situation where the path length differences between the top and bottom rays are equal to an integer multiple of the wavelength.

Similar to two-slit interference, $\tan \theta = y/L$ where y is the dark fringe location with respect to the centre and L is the distance from the slit to the screen. Be careful using the small angle approximation here. Check to see if the angles

are small enough first. If $\tan \theta$ differs from θ (in radians) by more than 5% you should not use the small angle approximation.

You may have noticed that the two-slit interference pattern you created in Activity 31.2 was really a combination of an interference pattern of small spots and a wider diffraction pattern. As mentioned previously, this is due to the non-zero width of the slits in the interference experiment.

For the following activities you will need:

- Optics Kit
- He-Ne Laser with mount
- Post-it notes, 3"×5"

 Activity 31-3: Diffraction Patterns

(a) Align single slit A in the laser beam and observe its diffraction pattern. This is a single slit with the same width as the double-slits used in the last activity. What similarities and differences do you see between this pattern and the ones you saw in Activity 31.2? Record your observations below and try to explain what you see.

(b) Now measure the locations of the first two dark fringes on either side of the broad maximum. See Figure 31.9. Record your results in the table below.

| m | y-left | y-right |
|----------|---------------|----------------|
| 1 | | |
| 2 | | |

(c) Measure and record the distance between the slit and the screen L .

(d) From your values for y and L , determine the angles θ where the dark fringes occurred.

| m | θ-left | θ-right |
|----------|---------------------------------|----------------------------------|
| 1 | | |
| 2 | | |

(e) Average your two angles for each order m and then use Equ. 31.3 to determine the slit width a for each order. (The wavelength of the He-Ne laser light is 632.8 nm.) Record your results below. How do your two values for a compare? How does the average of your two a values agree with the “true” value provided by your instructor? Calculate a percent difference between your average and the true value.

(f) Repeat steps (b)-(e) to determine the slit width of aperture C. Record your data in the tables below and show all of your work in the space provided.

| m | y-left | y-right |
|----------|---------------|----------------|
| 1 | | |
| 2 | | |

| m | θ-left | θ-right |
|----------|---------------------------------|----------------------------------|
| 1 | | |
| 2 | | |

(g) According to your results, which slit is wider? Write a short statement below about how diffraction patterns vary with slit width.

 Activity 31-4: Two-dimensional diffraction patterns

(a) Shine the laser through aperture H on the diffraction plate. This aperture consists of two crossed slits of the same width we have used previously to create an interference pattern. Try to explain in words the pattern you see. Sketch it below.

(b) Shine the laser through aperture J. This aperture contains a 15x15 array of circular apertures (0.06 mm dia.). Try to explain in words the diffraction pattern you see. Sketch it below.

(c) Now shine the laser through aperture I which contains 225 random circular apertures (0.06 mm dia.). How does this diffraction pattern differ with what you saw in part (a)? Try to explain any differences you see.

The Diffraction Grating

A diffraction grating contains many equal-width slits aligned parallel to each other at a fixed spacing. Diffraction gratings produce patterns that are sharper and where the bright fringes are more clearly separated than what you would see with two slits of the same separation d . A diagram of a grating created from putting grooves in a glass plate is shown in Figure 31.10. As with two slit interference patterns, the maxima of the a pattern created by a diffraction grating appear at locations corresponding to the following relationship:

$$d \sin \theta = m\lambda, m = 0, 1, 2, \dots \quad (31.1)$$

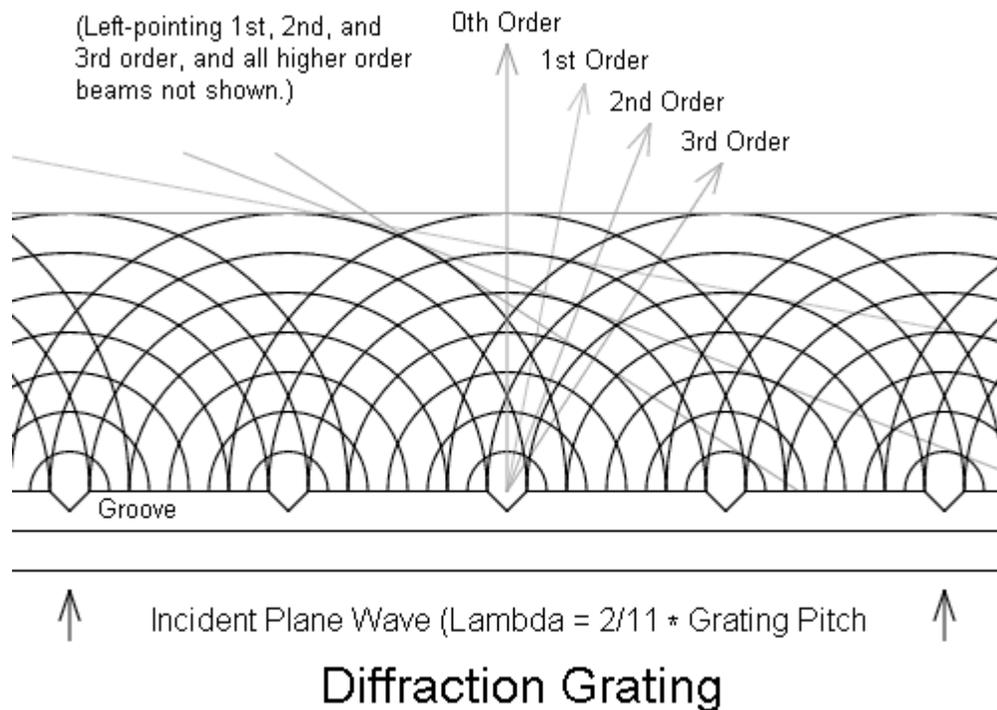


Figure 31.10: Creation of fringes using a diffraction grating.

Diffraction gratings are used in devices called spectrometers to display light spectra. In the next activity you will build your own spectrometer and then use it to examine the spectra of various light sources. In the following Unit we will learn about the quantum origins of atomic spectra and use this theory to understand the patterns seen in atomic spectra.

✍ Activity 31-5: A Diffraction-grating Spectrometer

(a) Put the diffraction grating from your optics kit in the laser beam and make sure it is straight with the rulings vertical and the label horizontal. Move the diffraction scale close to the grating by hand so you can see the various orders of diffraction from the grating. Move the Post-it note screens to the ends of the diffraction scale and mount the scale at a distance which gives clear first-order spots near the 10-12 cm marks. From the positions of the spots, the grating-screen distance and the laser light wavelength calculate the grating line spacing using equation 31.1. How does your calculated spacing compare the spacing indicated on the label of the grating?

(b) Calculate the positions where the following wavelengths of light should fall on the Diffraction scale: 400 nm, 450 nm, 500 nm, 550 nm, 600 nm, 650 nm, 700 nm. Record your results in the table below.

| Wavelength (nm) | Position on Scale |
|-----------------|-------------------|
| 400 | |
| 450 | |
| 500 | |
| 550 | |
| 600 | |
| 650 | |
| 700 | |

(c) Make a wavelength scale on the Post-it notes using these calculations and then check your calibration by shining the laser beam's first order spot on the home-made scale. If the spot does not fall near 630 nm, adjust the diffraction scale–grating distance until it is correct.

(d) Turn off the laser, unplug it and remove it from the optical bench. **Put the incandescent light source at the opposite end of the optical bench** (not where the laser was) so it shines through the hole in the diffraction scale. Make sure you do not have a Post-it over the hole. Centre the slit mask over the diffraction grating on the other side of its component holder. Turn on the incandescent light source and view its spectrum by looking through the diffraction grating towards the scale you made. This geometry is different than that for projecting the pattern with a laser but the angles you see are the same. Describe what you see when you look at one of the two wavelength scales you have created. Try to estimate the wavelengths of all of the spectral colours you see: red, orange, yellow, green, blue, violet. Record your results below.

(e) Put the coloured filters over the light source one at a time and record the spectral range of each filter.

(f) Remove the incandescent light source and try to look at the spectrum created by a florescent light. (You can use one of the white-board lights if the room lights are off or go out into the hallway.) How does this spectrum differ from that of the incandescent light? Do you have any idea why there is a difference?

(g) Record the grating, screen and post-it scale locations for your spectrometer below before you dismantle it. You will need this information to reconstruct your spectrometer at the beginning of the next unit.