

Fraunhofer and Fresnel Diffraction in One Dimension

Introduction

The simplest and most commonly described examples of diffraction and interference from two-dimensional apertures are those for which the light incident on the apertures and the light after passage through the apertures can be described as plane waves. In this limit the diffraction is described as **Fraunhofer** or **far field** diffraction. If one of the aperture dimensions is very small compared to the other – an example would be a slit with a width small compared to its length – the intensity of the light transmitted through the aperture and observed some distance away will vary in a direction perpendicular to the slit width and the light beam, but will be constant in a direction along the slit. Thus the variation in the pattern can be described by only a single dimension and it is called one-dimensional.

Fraunhofer diffraction has a particularly simple mathematical description. The *amplitude* of the diffracted wave can be described as the Fourier transform of the aperture function (For this experiment a suitable aperture function is one that is a constant equal to 1 over the aperture and 0 elsewhere). It is, of course, the *intensity* that is observed. Because it is most convenient to treat the amplitude as a complex quantity, the intensity or irradiance is proportional to the amplitude times its complex conjugate.

For many examples of diffraction, the light source and the point of observation are sufficiently far from the diffracting aperture that both the incident and diffracted light can be treated as plane waves. If these conditions are met the diffraction is described as Fraunhofer or far field diffraction.

If the condition that the light source and point of observation are far from the diffracting aperture is not met, so that one cannot employ the approximation of plane waves, then the curvature of the wavefront must be considered in deriving the diffraction pattern. This diffraction is described as **Fresnel** or **near-field** diffraction. (Fresnel is pronounced “*Fray-NEEL*”.) The mathematics involved in Fresnel diffraction is not as simple as the Fourier transforms of far-field diffraction. However, a description has been developed in terms of what are called Fresnel zones, that will yield understandable, qualitative results. If more quantitative answers are needed, special integrals called Fresnel integrals must be evaluated. This can either be done numerically or graphically with the aid of a Cornu spiral.

In this experiment, you will first observe far-field diffraction by the use of a lens which will collimate the light so that it hits the diffracting aperture as an approximate plane wave. Then you will remove the lens, and study near-field diffraction.

References

1. Hecht, *Optics* (4th or 5th ed.), Section 10.2, Fraunhofer diffraction.
2. Hecht, *Optics* (4th or 5th ed.), Section 10.3, Fresnel diffraction; Section 10.3.7, the Cornu spiral.

1 Apparatus and Initial Setup

The light source is a helium-neon laser ($\lambda = 632.8$ nm). A spatial filter consisting of a microscope objective and a 25μ pinhole with three micrometer positioning screws is used to clean up the beam. In the Fraunhofer diffraction part, the spatial filter is followed by a long focal length collimating lens. A high-resolution detector is used to record the diffraction pattern. The detector is a Hamamatsu S3923 MOS linear image sensor. It consists of 1024 photodetector elements called *pixels* 0.5 mm high and arrayed along a line with a separation of $25\mu\text{m}$ between the centers of adjacent pixels. It is important to align the array so that the entire diffraction pattern falls on the detector array and the plane of the array is perpendicular to the light beam.

The laser beam alignment needs to be checked first and then the spatial filter assembly positioned and adjusted.

Laser Alignment – Check that the base of the red HeNe laser is secured to the tabletop. With no objects in the beam path (except the detector assembly at the opposite end of the table), check that the laser beam is parallel to the table surface at a height of 6 inches. To do this, first place one of the alignment screens at a point farthest away from the laser directly in front of the detector, and then put another screen in front of the laser as close as possible to it. Notice the line-cross with the horizontal lines at exactly 6 inches above the table top. If the beam does not hit the screen on the 6 inch line, adjust the *front* positioning screws (on the underside of the laser mount, toward the beam end of laser) so that the beam hits the line. Now remove the screen closest to the laser and see where the beam hits the screen that is far away. If the beam does not hit that screen on the 6 inch line, adjust the *rear* positioning screws (toward the power line end of laser) so that it does. Then replace the screen that you just removed, and **repeat this procedure** (adjust the front screws when the screen is close, and the back screws when the screen is far away) until the beam hits the 6 inch line at all distances from the laser.

Leave the far screen in place to be used as a reference for aligning the other optical components. It is helpful to position the far screen so that the laser hits the center of the cross.

Spatial filter alignment – Check that the pinhole has been removed from the spatial filter holder. The pinhole is the small square metal piece with the handle. The thin metal disk at the center of the square piece is very fragile and any contact with it should be avoided.

Leaving room in front of the laser for the polarizer, place the spatial filter assembly in the beam path about 10 hole spaces (about 30 cm, see Figure 1) from the front of the laser so that the laser beam passes through the microscope objective and forms a disk of light centered on the cross at the far screen. Note that the horizontal position of the spot is affected by both the angle of the assembly with respect to the beam and its horizontal position. To get the correct alignment, set the angle so that the beam reflected from the inside surface of the microscope objective shines back on the aperture of the laser and also centers the diffuse beam on the cross. Check that the height of the beam hits the 6 inch height. If the beam is not at the correct height, adjust the back supporting screws on the laser mount slightly.

Once the disk of light is appropriately centered, clamp the spatial filter assembly to the desktop. Notice the three micrometer adjusters. The one that points towards the laser (along the same direction as the beam) controls the position of the microscope objective relative to the pinhole. To start, set this micrometer to about the 5 mm mark (the exact value does not matter).

Retrieve the pinhole holder from its storage box and examine it carefully. Notice the small step-edge along one side and the conical hole. The conical hole is the *front* of the pinhole holder and

should face the the detector. The pinhole itself is in the delicate metal foil attached to the back of the mount. Do NOT touch this foil. The step edge is the *top side* of the pinhole holder and should rest against the front edge of the top (vertical) micrometer shaft. Now put the pinhole in place at the ends of the micrometer shafts (which are magnetic) with the pinhole handle horizontal and with the conical part of the pinhole facing away from the laser.

Place a small screen a few inches (about 8-10 cm) in front the spatial filter assembly and use the micrometer handles to move the pinhole vertically and horizontally until you see some light on the screen. Once you begin to see some light, it is easy to optimize the vertical and horizontal adjustments to maximize the transmitted light. When the transmitted light is maximized, the light pattern on the screen should be centered very near to 6 inches in height. Use the third micrometer handle to move the microscope objective toward the pinhole so that the disk of light gets brighter. As you make this adjustment, you will need to readjust the horizontal and vertical pinhole centering micrometers slightly. You should see the transmitted light get brighter as the lens moves towards the pinhole. The interference rings will seem to disappear when the lens is correctly positioned relative to the pinhole, so that you see only a featureless symmetrical blob of light on the screen. The micrometer for the lens should be close to the 8.2 mm mark. Be careful to avoid having the end of the objective run into the pinhole. A good check of the position of the lens is the extreme sensitivity of the pinhole position on the light pattern: by slightly moving the horizontal or vertical micrometers, the bright disk should not move but should be extinguished. If the blob appears to move (up or down, left or right) the position of the microscope lens is not yet correct.

Detector Alignment – First place the polarizer in the beam between the laser and spatial filter (refer to Figure 1). Rotate the polarizer using the small handle and notice what it does to the light intensity. At one setting the laser light should appear quite dim, and at another, nearly as bright as it was without the polarizer. Set the polarizer to transmit maximum light.

Now, position the linear array so that the front of the array housing is approximately 90-95 cm from the front of the spatial-filter pinhole. Orient the base so that the track is perpendicular to the beam path and clamp the array assembly in place with the magnetic base. Turn on the array controller box and press the RESET switch so that the green LED labeled ACQ. (ACQUIRE) is on. Turn on the oscilloscope used to monitor the array output, and adjust it, if necessary, to obtain a trace.

Without any other object in the beam, you should see a broad “hump” on the oscilloscope screen. If the beam is too bright, the detector pixels may saturate. If this happens, move the polarizer into place between the laser and spatial filter, and adjust the polarizer angle to reduce the beam intensity. Center the hump in the detector by moving it horizontally along the track. Once it is centered, clamp the detector in place.

2 Fraunhofer Diffraction

In this part you will obtain the intensity pattern for laser light after it has passed through a single slit, sets of double slits with different ratios of slit width to slit separation, and a multiple slit pattern of either 3, 4, or 5 slits. The detector will give you digital values for the integrated (over time) intensity of the diffracted light at 1024 points in the diffraction pattern. You will acquire the data electronically and plot it out using a program of your choice (such as Excel). From the plots, you will manually extract the relevant experimental parameters and their uncertainties.

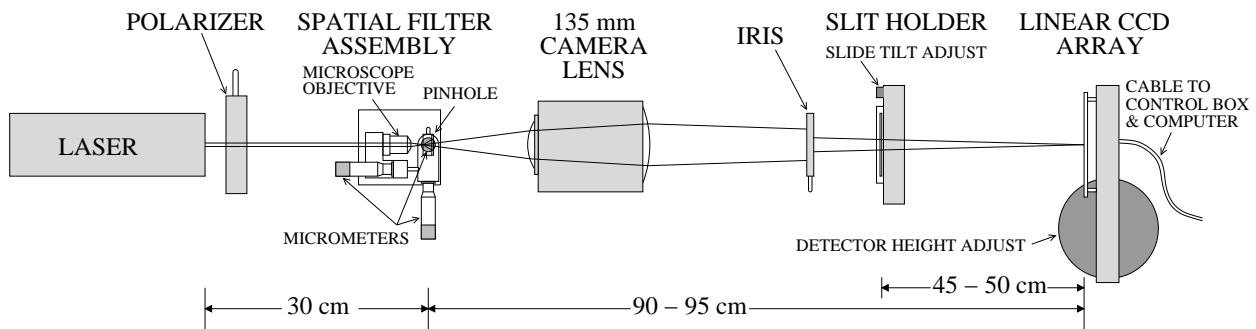


Figure 1: Setup for Fraunhofer diffraction. Distances are approximate.

2.1 Procedure for Fraunhofer diffraction

A camera lens is used to bring the laser light from the pinhole to “simulate” plane-wave propagation as it passes through the diffraction apertures. The lens thus enables a practical (tabletop) realization of Fraunhofer diffraction.

[Note for the curious: This setup is not quite the arrangement depicted in Fig. 10.3 of Hecht, in that the waves which impinge on the diffraction aperture in our experiment are *not* plane waves, but are *converging* toward the focus point on the screen. It can be shown, however, that our setup is optically equivalent to the ideal one where the light source and observation screen are both effectively at infinity; see the related discussion in Hecht, section 10.1.2.]

Before moving the 135 mm camera lens into position, be sure the detector is blocked with a screen so that the focused laser beam does not fall directly on the array. Allowing the unattenuated focused laser beam to fall directly on the array may damage it. The array chip costs \$800, so please treat it kindly. The array should also be blocked when you are changing the slides holding the diffracting apertures, as the focused beam can fall directly on the array during this process.

Place a screen directly in front of the detector array so that the diffuse beam is centered on the cross. Position the back of the camera lens 6-9 cm from the pinhole, and orient it so that the spot is (roughly) centered. Then slide the lens assembly slowly on the table, along the beam path, until the spot is tightly focused on the screen right at the center of the cross. Finally, adjust the height of the lens (with adjusting ring on vertical stage supporting the lens) and angle so the light falls on the screen at the center of the cross, and clamp the lens to the table with the magnetic base.

Move the slide holder into the beam path. Put the slide with the single slits in the slide holder and adjust the holder position and iris opening so that the widest slit is evenly illuminated; the

distance from the slide to the detector should be about 45-50 cm. Remove the cover over the array, and adjust the array position horizontally and vertically (with the adjusting ring on vertical stage supporting the array) so as to obtain a readout of the diffraction pattern on the oscilloscope. To prevent saturation of the array (indicated by a flat line at the top of the readout) it may be necessary to reduce the light intensity with the polarizer. If you have not already done so, move the polarizer in place between the laser and the spatial filter assembly and rotate the polarizer so that the readout on the scope shows no sign of saturation.

Place the iris between the lens and the slide holder rail so that it is concentric with the disk of light coming from the lens and 2-3 inches (5-8 cm) in front of the slide holder. Adjust the iris so that the disc of light is just big enough to hit only one slit pattern (about 4 mm in diameter). Illuminating more than the desired slit or set of slits will result in a diffraction pattern with a very high spatial frequency (try it). Why is this so?

After you see a good pattern on the scope, the vertical sensitivity and horizontal sweep speed on the scope may need to be adjusted to view the readout optimally. Once you observe a pattern, you can adjust the angular position of the slide (small knob at upper left corner of slide holder, called "slide tilt adjust" in Fig. 1) to maximize the symmetry of the detected pattern. To achieve maximum symmetry, it is sometimes useful to look in detail at the part of the pattern away from the central maximum. This can be done by increasing the light intensity (by adjusting polarizer) and/or increasing the vertical sensitivity on the scope. Finally, check the vertical adjustment of the array to make sure it is not at the top or bottom edge of the diffraction pattern.

Note: the symmetry of the pattern is affected by many things. Generally, you get the best results numerically by optimizing the arrangement to give the highest symmetry. It is important to have all optical components aligned with the center of the beam, so it is best to first adjust the beam and detector so that the undiffracted beam is centered, and then adjust the iris and slit position to follow this center.

A comment on the array output: the analog signal that comes from the array controller is a series of 1024 voltage levels, with each voltage level being proportional to the intensity (integrated) of the light falling on the associated element, or pixel. By increasing the sweep speed on the oscilloscope you can expand the display and see the voltage levels for individual pixels. The maximum output voltage is about 4.0 volts. When the output for a given pixel (or series of pixels) approaches that level, it is said to be saturated. This means that the output no longer increases and is not proportional to the intensity of the light falling on that particular pixel.

With all the optics in good alignment and with the desired diffraction pattern displayed on the scope, you are now ready to record the diffraction pattern on the computer. Detailed instructions for recording the diffraction pattern on the computer are available in the lab.

2.2 Single slit diffraction

Obtain separate diffraction patterns for *two* single slits with different widths and record the data on the computer.

Record the necessary additional information you will need in order to analyze the patterns you obtain. You will need additional distances and the wavelength of the laser light (see more information below).

Use the computer program to plot the data, or download the data set (a simple two-column text file) and plot it using your plotting program of choice (such as Excel). Then obtain the physical

parameters from the graph directly. There is no need to make a computer fit to the pattern; indeed the physics is better understood by measuring the graph by hand with a ruler.

For one slit, you should find (from the graph) information that you may use to calculate the slit width and its associated error. The width of the central peak and the location of the minima on either side should both be used to obtain your results. You will need a number of experimental parameters, such as the wavelength of the laser, the slit-to-array distance and the horizontal scale of the detector. The laser wavelength and the horizontal scale (pixel to pixel spacing) have already been given. Use a tape measure to measure the distance from the slits to the detector. **Be careful to avoid any contact with the front of the detector.** Use standard propagation-of-error techniques to determine the error on the slit width. Comment on the agreement between your derived values and the actual values of the slit width (available in the lab).

2.3 Double slit diffraction

Select *two* sets of double slits with different ratios of slit width to slit separation. Obtain and record data sets for each.

Using the same techniques as earlier, obtain the slit widths and slit separations from the plotted data; comment on the agreement with the actual values.

2.4 Multiple slit diffraction

Select *at least one* from the 3, 4, or 5 slit apertures. Obtain and record a data set for the aperture of your choice.

Using the same technique as above, obtain the slit widths, separation, and number of slits from the plotted data. (The slit number can be obtained by measuring the width of the fringes and comparing it to the fringe separation, rounding off to nearest integral value.) Comment on the agreement with the actual values.

3 *Fresnel Diffraction*

In this part two examples of Fresnel diffraction will be observed and compared to theory: diffraction from a single slit (illustrating the transition from Fresnel to Fraunhofer diffraction), and diffraction from a straight edge.

3.1 Procedure for Fresnel diffraction

The apparatus is essentially the same as that used for Fraunhofer diffraction. In fact, the first objective is to study how the Fraunhofer pattern for a single slit becomes Fresnel-like as you widen the slit.

Remove the camera lens and iris used in the Fraunhofer diffraction part of the experiment and set it gently aside. Slide the slit holder on its track so that it is no longer in the beam. Check the position of the linear array so that the front of the array housing is approximately 90-95 cm from the pinhole on the spatial filter.

The light which will hit the aperture is no longer traveling in (approximate) plane waves, but

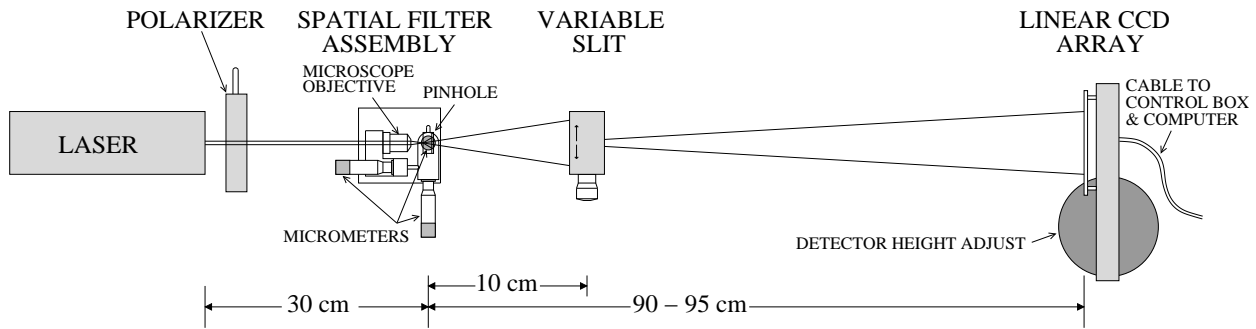


Figure 2: Setup for Fresnel diffraction.

has wave fronts whose curvature depend on the focal length of the microscope objective and the distance between the pinhole and the slit. (Here, we will only use a single slit or straight edge.)

Place the variable slit approximately 10 cm in front of the pinhole (see Figure 2), and adjust its position so the slit is uniformly illuminated and the diffraction pattern is the right size to fill the array. To prevent saturation of the array (indicated by a flat line at the top of the readout) it may be necessary to reduce the light intensity with the polarizer.

With all the optics in good alignment and with the desired diffraction pattern displayed on the scope, you are now ready to record the diffraction pattern on the computer.

3.2 Single slit diffraction

First determine where the transition from Fraunhofer to Fresnel diffraction occurs as you change the slit width with the micrometer on the variable slit. (Hint: the Fraunhofer pattern is the square of a “sinc” function $[\sin(x)/x]$: the minima are all zero. These minima change when the slit is opened enough to require a Fresnel interpretation). Record the approximate slit width when this transition takes place and later determine whether it agrees with the theory. *Obtain a 1024 point readout of the intensity pattern using the LabVIEW program.*

Carefully record all relevant distances and dimensions. In this case, you need to have the numbers necessary to calculate the *reduced slit width* u (or v); see Hecht section 10.3.6 for definitions and an explanation.

Next, reduce the slit width to the Fraunhofer regime and use the techniques described in the Fraunhofer write-up to determine the slit width. The pattern should include the central maximum plus three secondary maxima on both sides. *Obtain a 1024 point readout of the intensity pattern using the LabVIEW program.* Carefully record all relevant distances and dimensions, as before.

Finally, starting from the Fraunhofer regime, increase the slit width and note that there are a number of discrete widths (in the Fresnel regime) where the central point in the intensity pattern goes through a minimum. *Record the slit widths for the first two or three of these minima and obtain a 1024 point readout of the pattern for each one.*

The analysis will use the Cornu spiral. Figure 10.72 in Hecht gives a labeled graph which can be used (Fig. 10.50 in 4th ed.). From your knowledge of the connection between the Cornu spiral and the intensity plot, it should be fairly obvious how one obtains the approximate slit widths corresponding to these minima. This procedure is approximate; the error estimate should involve

an educated guess of how well one can obtain the data from the graph. Be sure to convert the “Fresnel” units back to laboratory units using the formulas in the book or notes.

3.3 Diffraction by a straight edge

Widen the slit further and notice how the pattern approaches that for a single edge. Replace the slit with the thin, straight-edged piece of metal shim stock provided. It is on another stand and magnetic base. **BE CAREFUL: the metal edge is sharp and can cut!** *Obtain a 1024 point readout of the intensity pattern.* Carefully record all relevant distances and dimensions.

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