

# Diffraction and Interference of Plane Light Waves

## Introduction

In this experiment you will become familiar with diffraction patterns created when a beam of light scatters from objects placed in its path. Such experiments were important historically as they were crucial in establishing the wave nature of light in face of competing theories that described light in terms of geometrical rays of discrete objects. Only a wave theory can give a quantitative explanation of the complex phenomena of diffraction and interference. A more complete description of diffraction and interference phenomena can be found in textbooks such as in chapters 21 and 22 of "Physics for Scientists and Engineers" by Knight, or Chapter 29 of Bauer & Westfall. A review lecture is also available on the 192 web site.

## Theory Part I: Diffraction

When a plane light wave (in our case a laser beam) hits an obstacle it is diffracted. We can understand this phenomenon in terms of Huygens principle that states that every point in the wave front can be considered as a source of new wave fronts. This is illustrated in Figure 1 where a parallel beam of light strikes a barrier with a narrow slit and the diffracted wave can be considered to originate from a source at the slit.

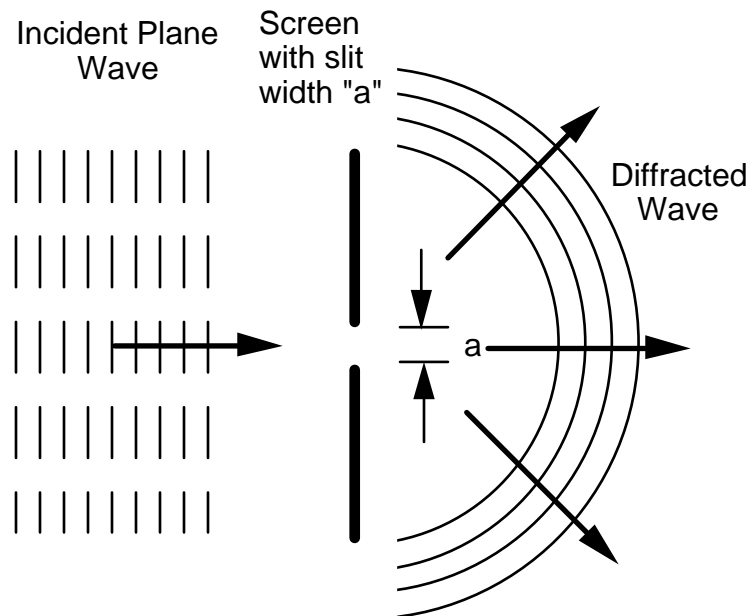


Fig. 1: Schematic representation of diffraction from a slit

After the slit, points of equal phase on the wave front are no longer in a plane but on concentric circles as indicated in the figure. This is exactly true in the limit where the slit width "a" goes to zero.

The result of this is that if we observe the image of the slit from a distance we will not only see a bright central image of the slit but, in addition, a pattern of light and dark areas around the central image. This pattern is called the diffraction pattern. Its origin is explained in Figure 2 where we consider two wave fronts leaving the slit at an angle  $\Theta$  with respect to the normal to the slit.

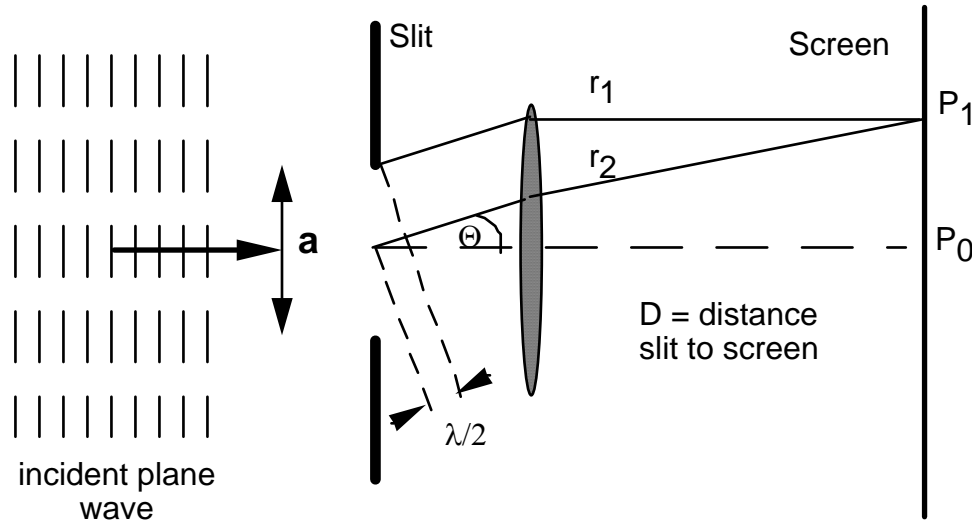


Fig. 2: Conditions for first minimum of diffraction from a slit

These two wave fronts have the same phase at the slit, one starting at the edge, the other at the center. We will observe the resulting intensity pattern on a screen a distance  $D$  from the slit, where  $D$  is large compared to the slit width " $a$ ". This is sometimes called Fraunhofer diffraction. This can be achieved by using a focusing lens or by choosing  $D$  to be large (1 - 2 m) as is done in this lab. If the two light rays in Figure 2 are out of phase by  $180^\circ$  (at the point of observation  $P_1$ ) the intensity at  $P_1$  will be zero, i.e. it will be dark. This is the case when the paths of the two differ by  $n \lambda/2$  where  $n = \pm 1, \pm 2, \pm 3$  etc. and  $\lambda$  is the wavelength of the light. So for the case shown, the condition for  $P_1$  to be dark is:

$$a/2 \sin \Theta = n \lambda/2 \quad (1)$$

Therefore, we will find diffraction minima at the following angles:

$$\sin \Theta = n \lambda/a \quad (2)$$

with  $n = \pm 1, \pm 2, \pm 3$  etc. For a single slit, the diffraction pattern intensity  $I$ , as a function of the angle  $\Theta$  is given by (Halliday and Resnick, Ch. 41):

$$I \sim (\sin \alpha/\alpha)^2 \quad (3a)$$

where

$$\alpha = (\pi a /\lambda) \sin \Theta \quad (3b)$$

The observed intensity distribution, given by Eq. 3 is displayed in Figure 3 for different values of "a" in terms of the wavelength  $\lambda$ .

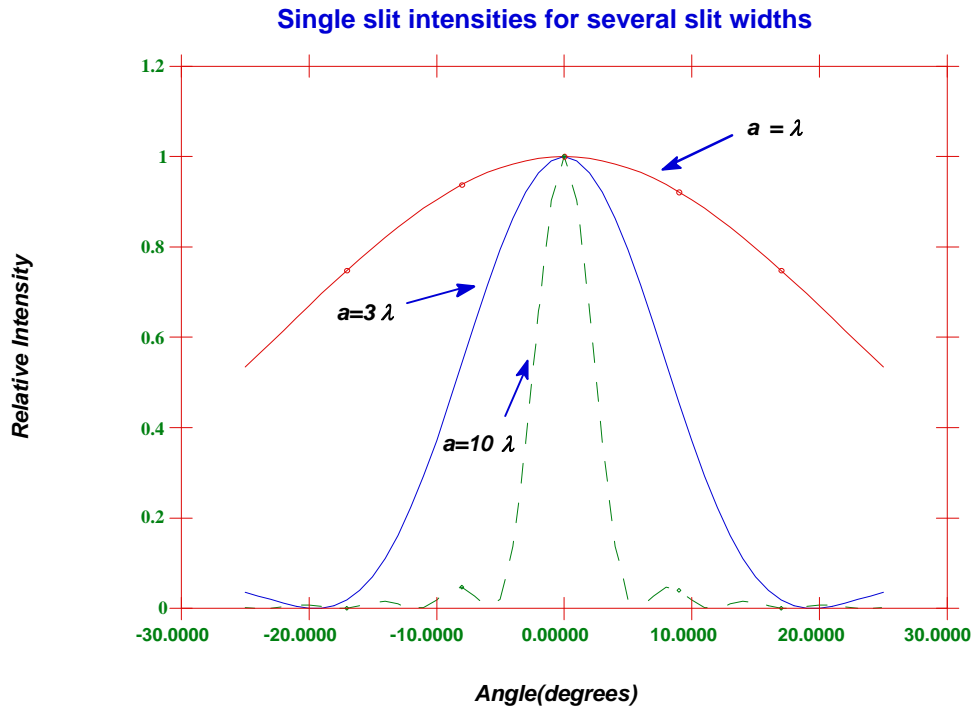


Fig. 3: Intensity patterns for single slit diffraction.

The intensity in the higher order maxima is much less than the central peak. Another feature is that with increasing slit width, the central peak becomes narrower and the secondary maxima more pronounced.

## **Theory Part II: Diffraction and Interference**

### **Double Slit Interference**

Up to this point, only single slits have been discussed and now we want to turn to what happens in the case of multiple slits. For simplicity we will consider a plane wave falling onto a double slit consisting of slits  $S_1$  and  $S_2$  as indicated in Figure 4. Furthermore, we will assume that the width of these slits is negligible so that there is no diffraction from within each slit. Each of the slits will act as a source of light and waves originating from  $S_1$  and  $S_2$  will be coherent, i.e. in phase. The interaction of these two coherent waves is in general called interference and this interaction will give rise to an interference pattern (or fringes) on the screen, i.e. we will observe light and dark areas. Again, in Figure 4 a focusing lens has been drawn, whereas, in the lab the distance from slit to the screen,  $D$ , is large and thereby eliminates the need for such a lens.

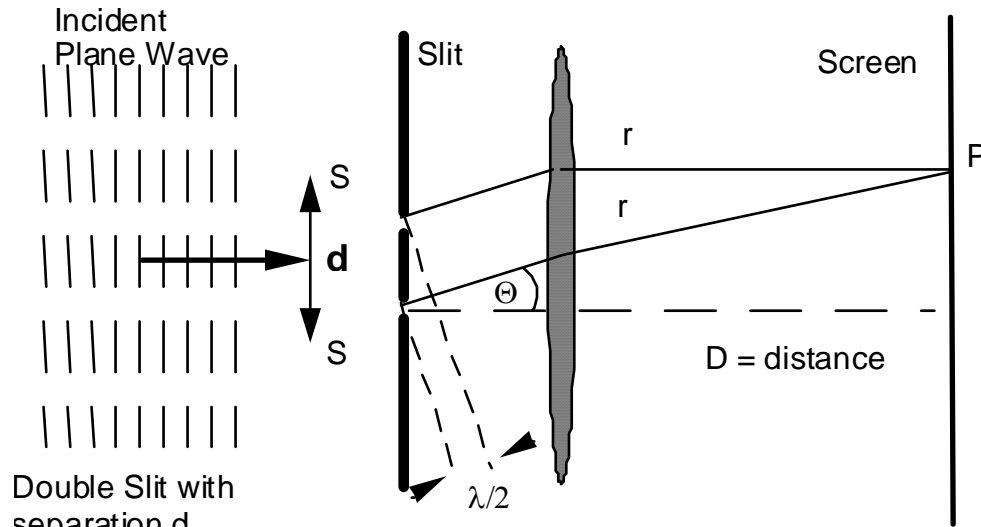


Fig. 4: Interference from a double slit.

In a fashion similar to the first part of the lab, the conditions for destructive (intensity = zero) and constructive (intensity = maximum) interference are simple. Destructive interference results when the two waves are out of phase by  $180^\circ$  which is equivalent to saying that their path length (between slit and screen) differs by  $n \lambda/2$ . If the distance between the slits is "d" then the condition for minima is :

$$d \sin \Theta = (n + 1/2) \lambda \quad n = 0, 1, 2, \dots \quad (4)$$

Similarly the condition for maxima is:

$$d \sin \Theta = n \lambda \quad n = 0, 1, 2, \dots \quad (5)$$

The intensity pattern will have a central maximum ( $\Theta = 0$ ) for  $n = 0$  which is called the 0<sup>th</sup> order maximum. Other maxima occur at angles given by  $n = 1, 2, 3, \dots$  etc. and "n" is called the order number.

The intensity distribution from the simplified double slit (assuming very small slit width) as a function of  $\Theta$  is given by (see Halliday and Resnick Ch. 41-7):

$$I \sim (\cos \beta)^2 \quad \text{with } \beta = (\pi d/\lambda) \sin \Theta \quad (6)$$

The distribution is shown in Figure 5a.

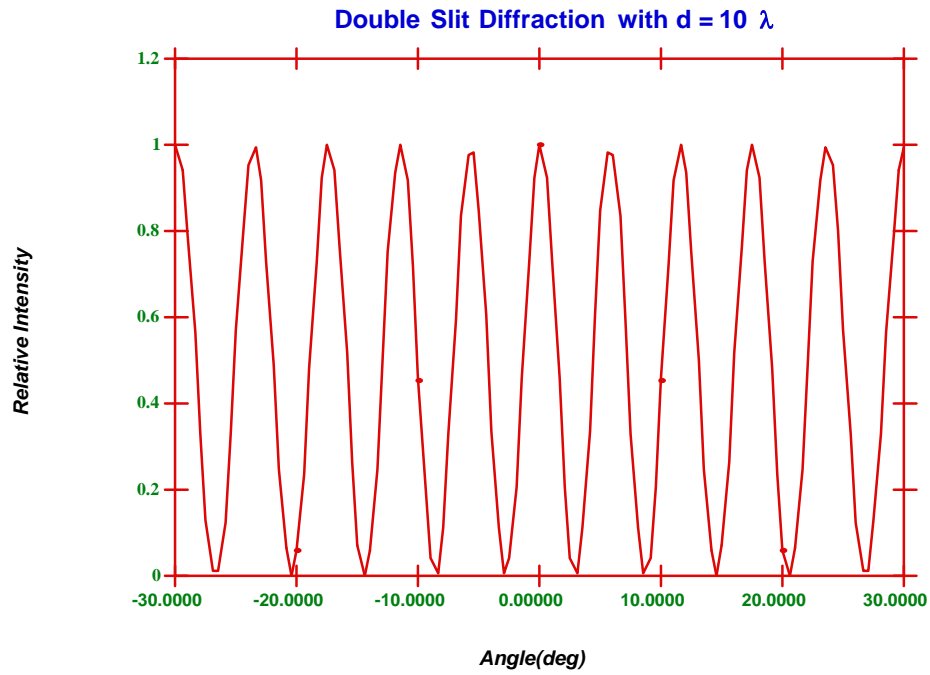


Fig. 5a: Diffraction from a double slit.

If we now allow the width of the two slits to be finite, diffraction will occur and the intensity distribution will be that given by Eq. 3 and shown graphically in Figure 5b.

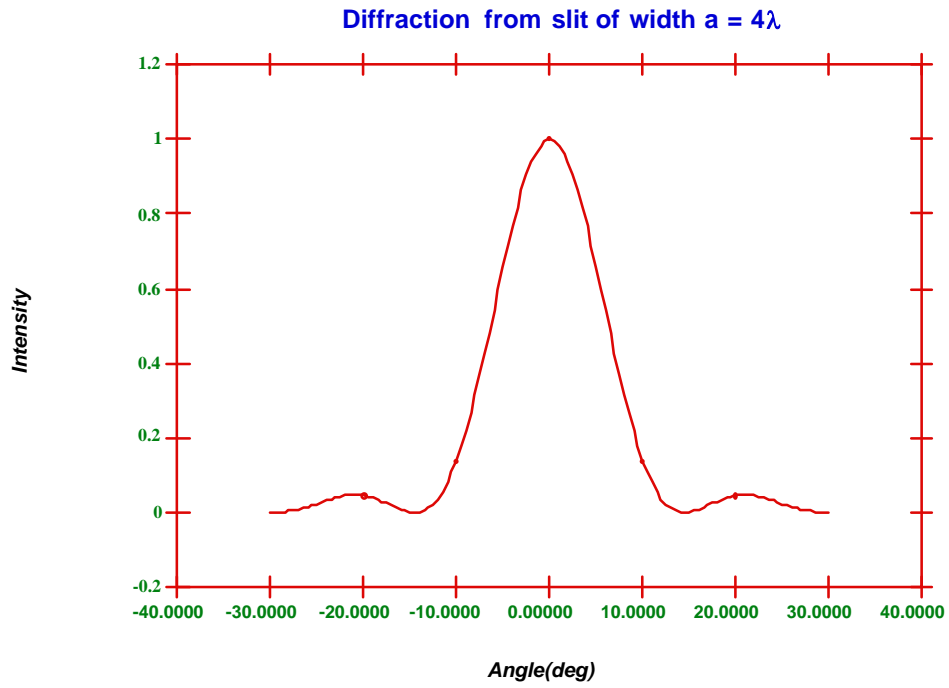


Fig. 5b: Diffraction from a single slit

The intensity distribution resulting from the combination of diffraction and interference is given by the product of Equations 3 and 6 and is displayed in Figure 5c.

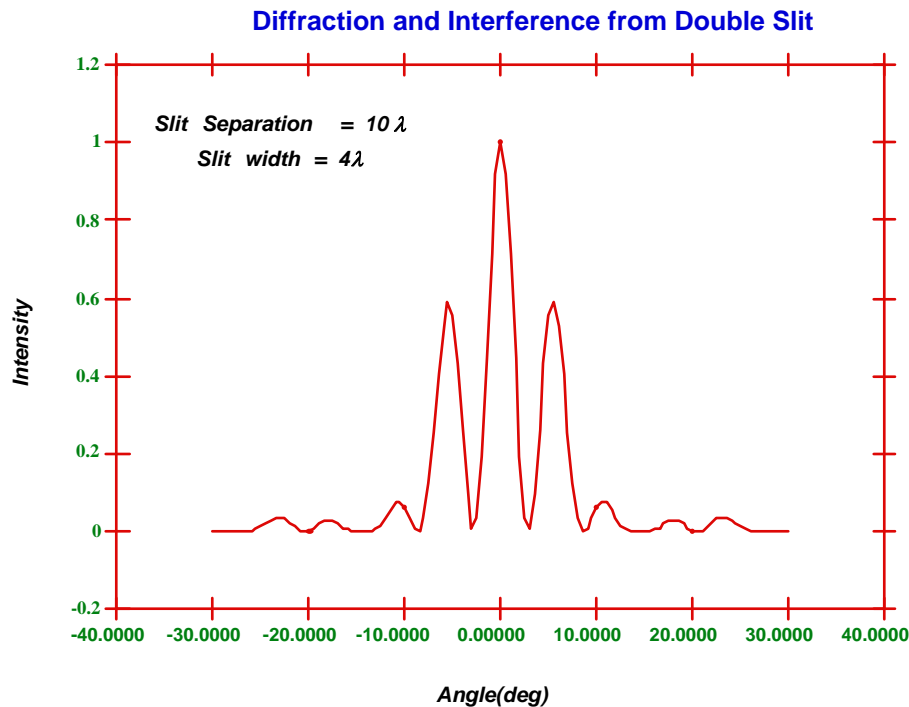


Fig. 5c: Diffraction and Interference from Double Slit

The envelope of the distribution is determined by diffraction, whereas, the internal structure is due to interference. Note, however, that the envelope depends critically on the width of the slit and, as expected, the influence of diffraction can be minimized by choosing very narrow slits (see Figure 3). In our example, diffraction creates a minimum in the distribution in the region of  $12^\circ$ .

### Multiple Slits

A logical extension of the double slit experiment is the multiple slit experiment where the number of slits is increased from two to some large number  $N$ . A particular multiple slit arrangement where the number of slits can exceed  $10^3/\text{mm}$  is called a diffraction grating. With increasing  $N$ , the interference fringes within the central diffraction envelope become narrower. The condition for maximum is still given by Eq. 5, but now "d" has become very small.

### ***Experiment: Part I***

A He-Ne laser produces monochromatic light (single wavelength) which is well collimated and coherent. The wavelength is 632.8 nm. Make sure your eyes are never exposed to direct laser light or its reflections.

#### **Single Slit Diffraction**

Set up a projection screen by taping a piece of paper to the box on the end of the laboratory table. Mount the slide, which contains several single slits of different widths in front of the laser so that a diffraction pattern is produced on the screen. Record the patterns for the four available single slits. Choose pattern C or D and record the locations of the minima.

1. From the pattern, the distance  $D$  from slit to screen and from  $\lambda$ , compute the slit width "a" and estimate your error in "a".
2. Compare your measurement with the value indicated on the slit.
3. Do the general features of the observed patterns and their dependence on the slit width agree with the predictions of Figure 3?

#### **Diffraction from a wire**

Replace the single slit with the metal/wooden box containing a thin straight wire.

**Question 1:** If you shine the laser beam on the wire, why do you expect to see a diffraction pattern? Think about the wire as being complementary to a slit.

From the diffraction pattern determine the diameter of the wire using the single diffraction formula for the location of the minima. Again estimate errors and compare to the given wire diameter.

Using this method measure the diameter of your hair.

### ***Experiment: Part II***

One of the slides contains 4 double slits with "a" and "d" varying. Repeat the procedure of part 1 for this set of double slits. From the observed pattern calculate both slit width and slit separation and their uncertainties for one set of slits. For the other 3 slits compare the observed patterns with your expectations based on a knowledge of "a" and "d". Measure minima for diffraction, maxima for interference.

### ***Experiment: Part III***

Repeat the above procedure qualitatively for the set of multiple slits with  $N = 2, 3, 4, 5$ . Comment on the spacing, width and brightness of the principal maxima for the four cases.

### ***Experiment: Part IV***

Repeat the procedure for two different "diffraction" gratings. In the lab, there should be gratings with 500 lines/mm or 1000 lines/mm. You may have to reduce  $D$  to observe the patterns. In any case, the angles involved may not be small. From the patterns calculate the grating spacing, "d", for each grating.