Experiment No- 1

Single slit and Double-Slit Diffraction Experiment

Aims of the Experiment:

1) To see the diffraction pattern produced by coherent light passing through single- and double-slit apertures.
2) To explore how the diffraction pattern depends on the size of the apertures and their separation (in case of double slit experiment).
3) To measure the slit width in case of single slit diffraction experiment.
4) To measure the slit width and slit separation in the case of double slit experiment using known wavelength of a coherent light source.

Equipments:

a) Optical bench and few sets of optical mounts.
b) Laser diode($\lambda_{red} = 650nm$ for red/ $\lambda_{green} = 532nm$ for green color) with power supply
c) Linear translator(a micrometer attached with the photo detector)
d) Light sensor (a highly sensitive photo detector)
e) Single Slit/Double Slit Set
f) ***Science Workshop*** interface unit together with a ***Data Studio software*** installed in a computer.

<u>Note: Do not stare directly at the laser or point the laser toward anyone else's eyes.</u>

Introduction:

Nowhere is the wave nature of light demonstrated more clearly than in the phenomenon of interference. Many kinds of waves exhibit interference: light waves, sound waves, water waves, and so on. The underlying physics is relatively simple: when several different waves arrive at the same point in space at the same time, they pass right through each other. But at the point where the waves overlap, the total wave strength there is just the sum of the individual wave's strengths at that point. We say that these waves obey the **superposition principle**.

If we restrict our attention to just two waves at a time, and make the assumptions that these waves have the same amplitude and frequency, then we can see two limiting cases of interest to us. When the waves are **in phase**, or in other words, when the oscillations of the waves match up exactly, we can see that the waves will **constructively interfere**, and the net wave amplitude will be doubled, as shown in **Fig. 1(a)**. If, at the other extreme, the two waves are exactly **180° out of phase**, the waves will **destructively interfere**. In this case, the net wave amplitude is zero, meaning that the waves have perfectly ‘***canceled***’ each other out, as shown in **Fig. 1(b).**

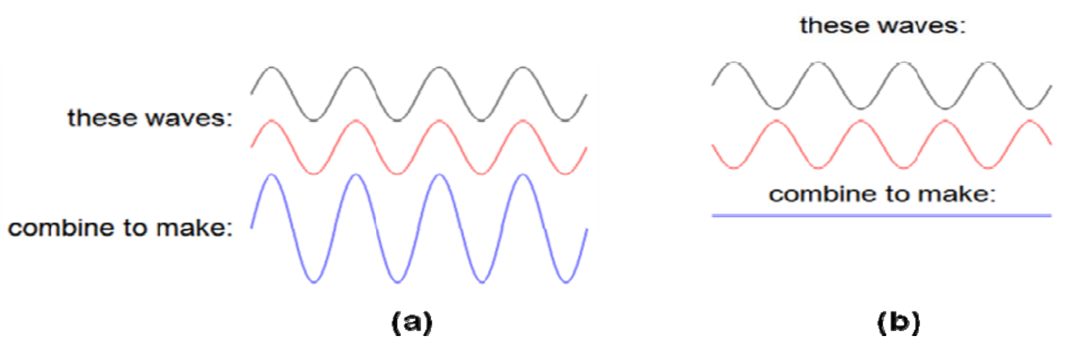


Fig. 1 Superposition of equal-amplitude, equal-frequency waves. In (a), the two waves are in phase, and the result is constructive interference. In (b), the two waves are 180° out of phase, resulting in destructive interference.

One way in which waves can drift out of phase with respect to each other is if they travel different distances to arrive at the same point. As a specific example, we observe that when **monochromatic, coherent** light passes through a narrow aperture (where “narrow” in this context implies that the width of the opening is comparable to the wavelength of the light), it spreads out into the region which we would classify as the “shadow” of the slit. (The shadow is the region behind the slit that light would not reach if it traveled perfectly straight lines.) The spreading of light after passing through an aperture such as this is known as **diffraction**. A top-down cartoon of this phenomenon is depicted in **Fig. 2** below.

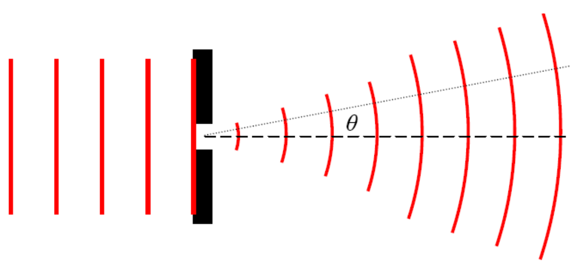


Fig. 2 Spreading of a wave as it passes through an aperture whose width is comparable to the wavelength of the wave is known as diffraction. The pattern will be most intense along the forward direction (represented as a dashed line.) We will be interested in how the intensity varies as we look at various angles θ away from the center.

As the light passes through each point of the opening, it spreads out in all directions, interfering, in some sense, with itself. In our minds, we imagine that each point in the opening is a new source of a “wavelet” of light. Due to their slightly different starting positions, each of these wavelets will travel minutely different distances to arrive at the same point in space. This will introduce a phase difference in the multitude of waves arriving at that location. Where the waves are generally all arriving out of phase with each other, the net wave amplitude will approach zero. Where the waves are generally arriving in phase, we expect the net wave amplitude to be large. With only a single slit, though, only points directly in front of the opening along the direction of propagation will generally arrive all in phase, so we expect to see a bright central spot, surrounded by fainter, alternating bands of bright and dark areas, where constructive and destructive interference occur, respectively.

Most wave sensors (*e.g.*, in humans, our "sound sensors" are our ears, which receive sound waves, and our eyes act as light sensors, receiving light waves) are sensitive to the *intensity* of the wave, rather than the amplitude. For most types of waves, the intensity is related to the *square* of the wave signal. In the present context of light waves, we relate intensity with brightness the brighter a light source is, the higher its intensity.

<u>Single Slit Diffraction experiment:</u> An optical setup for the diffraction experiment is shown in **Fig.3.** It consists of a coherent light source, a slit system and a light detection mechanism. In this experiment the diffraction profile is measured using a highly sensitive photo-detector by moving it to various positions of the diffraction pattern. The linear movement of the photo-detector is recorded by a rotary motion sensor.

Fig. 3 Experimental set up for the diffraction experiment.

When light passes through a single slit, it will create an alternating pattern of bright and dark fringes, which we could equivalently describe as an alternating pattern of high and low intensity, as shown in **Fig.4a**. The intensity profile of the single slit diffraction can be expressed as

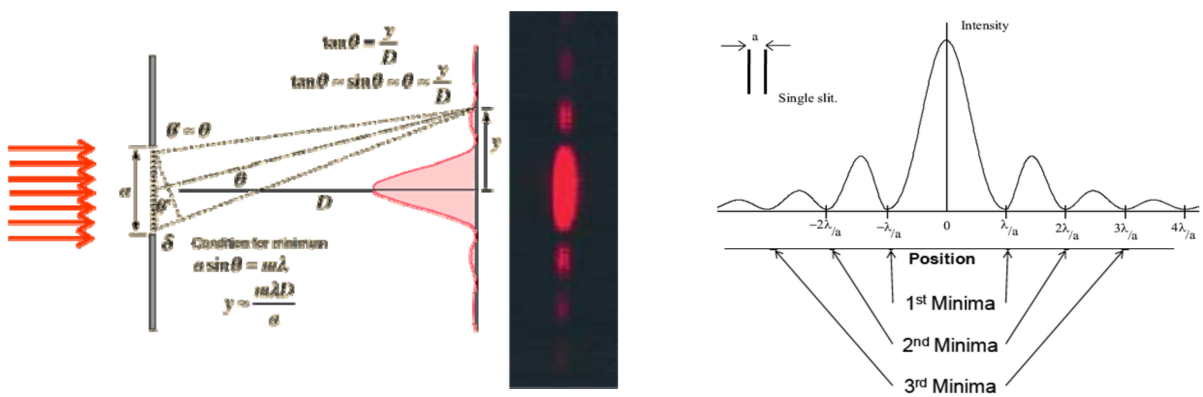
$$I(\theta) = I_0 \left(\frac{\sin \alpha}{\alpha} \right)^2 \tag{1}$$

where $I(\theta)$ is the intensity at a given angle θ, I_0 is the original intensity, and $\alpha = \frac{\pi a \sin\theta}{\lambda}$.

In the single slit diffraction pattern, the angular position of the maxima cannot be described via simple trigonometric expression, but the minima (dark spots) can. We find that the single-slit *minima* will be located at an angle θ away from the central maximum where θ must satisfy

$$a \sin\theta_m = m\lambda, \qquad \text{m=1, 2, 3, ---} \qquad (2)$$

with a representing the slit width, λ the wavelength of the light, and m is an integer which labels the minima, counting outward from the center as depicted in **Fig. 4b**. We will often choose to visualize an interference pattern by showing its intensity as a function of position, for instance, of a diffraction pattern shining on a screen.



(a) (b)

Fig. 4 a) Schematic of the single-slit diffraction Experiment. The single-slit diffraction pattern will consist of a large, central bright spot, flanked symmetrically by alternating dark and bright fringes. The central maximum will be at least ten times brighter than any of the side maxima, b) A zoomed-in display of the side maxima and minima. We count the minima outward from the central maximum, symmetric across the center.

In general, angles are more difficult to measure than distances, and so we will often not attempt to ascertain the *angular* position of the minima directly, but will rather focus on their *linear* position, at some constant distance D away from the slit. This arrangement is typically shown in a top-down view, as in **Fig. 5**. From that figure, we can see how to relate the linear distance y of a maximum or minimum relative to the central maximum and the angle θ that the maximum or minimum makes with respect to the central maximum. Using trigonometry, we can see that they are related by

$$\tan\theta = \frac{y}{D}, \tag{3}$$

By using both Equations 2 and 3, we can determine the slit width by measuring the linear position, y of the intensity minima produced by a single slit, distance between the slit and the detector, D and the known value of the wavelength of the light, λ in this experiment.

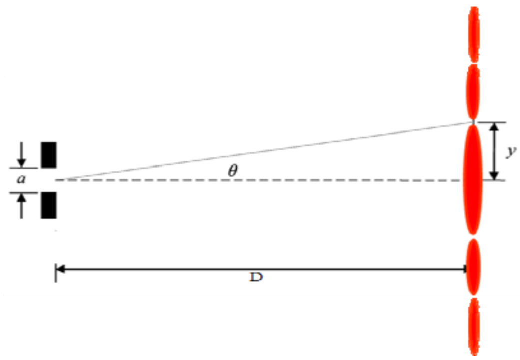


Fig. 5 Measuring the linear position of the 1st-order minimum to the left of the central maximum. The diffraction pattern produced by the single slit is allowed to shine on a detector (or screen) a distance *D* away from the slit. We can then measure the linear location of the minima, and using trigonometry, determine at which angles, with respect to the central maximum, these minima are located.

<u>Double Slit Experiment:</u> In the second part of the experiment, we will also explore the interference pattern produced by two slits, often known as **Young's double-slit experiment**, in honor of Thomas Young who performed this experiment in the early 19th century.

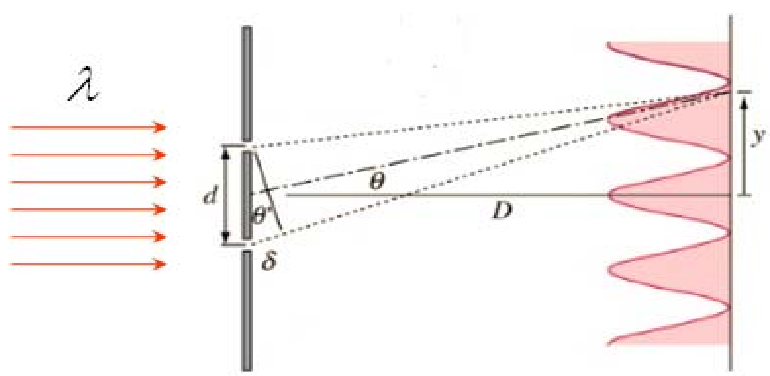


Fig. 6 Idealized double-slit intensity pattern as a function of position. This is the pattern we would see if the size of the individual slits is relatively small.

We will illuminate two narrow slits with the same monochromatic, coherent light source as before, but we now expect to see a different pattern. First of all, more light is now going to reach our screen, and so we expect the overall pattern to be brighter (more intense). But more interestingly, we now expect to see an interference pattern due to the fact that the light from the two slits will travel different distances to arrive at the same point on the screen. If we consider two very narrow slits separated by a small distance *d*, the diffraction of the light from each slit will cause the light to spread out essentially uniformly over a broad central region and we would see a pattern such as the one depicted in **Fig. 6**.

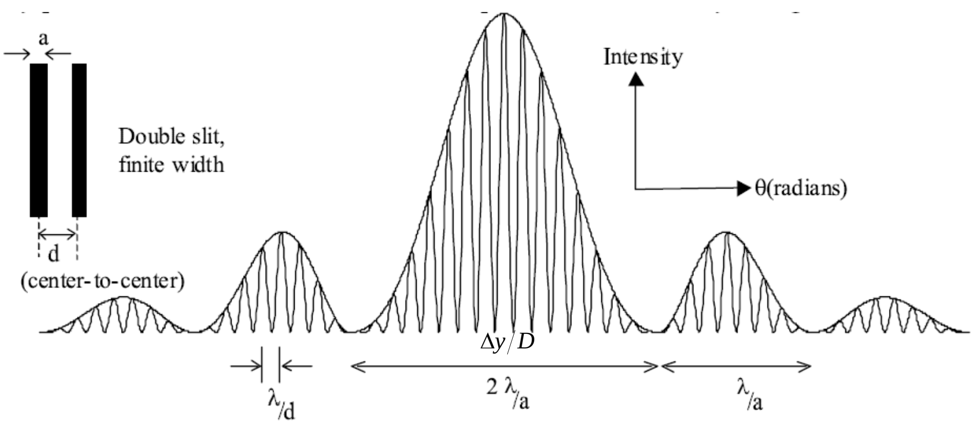


Fig. 7 Actual (non-ideal) double-slit interference pattern. The maxima and minima appear where constructive and destructive interference occur, respectively, due to the path length difference between the waves propagating from each slit to the observation point (screen). This pattern is attenuated by the single-slit "envelope". You can envision this pattern being created by multiplying the patterns in Fig. 4b and Fig. 6 together at each point along the axis.

If the individual slits are somewhat larger, so that the diffraction patterns are not so spread out, we would expect to see a somewhat more complicated pattern, which shows both the diffraction pattern and double-slit interference pattern simultaneously, as depicted in **Fig.7**. In both cases, the maxima and minima will appear where the conditions for constructive and destructive interference are satisfied, respectively

If the width of the slits a and the separation between the slits is d , the Fraunhofer diffraction gives the intensity of the diffracted light as,

$$I(\theta) = I_0 \cos^2(\beta).\left(\frac{\sin\alpha}{\alpha}\right)^2 , \qquad (4)$$

where $I(\theta)$ is the intensity at a given angle θ, I_0 is the original intensity, $\beta = \frac{\pi d \sin\theta}{\lambda}$ and $\alpha = \frac{\pi a \sin\theta}{\lambda}$.

In this case, the intensity *maxima* will be located at an angle *relative* to the central maximum, where θ will obey the relation

$$d \sin\theta = n\lambda, \qquad n = 0, 1, 2, 3, \qquad (5)$$

The intensity *minima*, on the other hand, due to the double-slit interference will occur at an angle θ relative to the central maximum given by

$$d \sin\theta = \left(p + \frac{1}{2}\right)\lambda, \qquad p = 0, 1, 2, 3, \qquad (6)$$

As described in **Fig. 7**, The width of the slit (a) in the case of double slit interference experiment can be determined by measuring the angular width ($\frac{\Delta y}{D}$) of the principle maxima of the diffraction envelop, i.e.,

$$2\theta = \frac{2\lambda}{a} \Rightarrow \frac{\Delta y}{D} = \frac{2\lambda}{a} \qquad \text{(for small } \theta\text{)} \qquad (7)$$

and the separation between the slits (d) can be calculated from the difference of angular width of two successive minima (or maxima) of the interference pattern, given by,

$$\sin\theta_{p+1} - \sin\theta_p = \frac{\lambda}{d}$$
$$\Rightarrow \left(\frac{y_{p+1}}{D} - \frac{y_p}{D}\right) = \frac{\lambda}{d} \qquad (8)$$

Please note that **Eq. 2**, which describes the necessary condition for *minima* to appear in a single-slit diffraction pattern, looks qualitatively the same as **Eq. 5** which describes the necessary condition for *maxima* to appear in the double-slit interference pattern. They describe very different scenarios, and you should make every effort to keep them distinct in your mind.

Directions:

In this experiment, a laser diode will produce a continuous, coherent light source, which will shine through a small aperture, or slit. At the opposite end of the optical bench, a light sensor (detector) is set up that will measure the brightness (intensity) of the light shining onto that point in space. Record the light intensity using computer controlled **Data Studio software** and by moving the light sensor from one side (preferably, from 3rd minima on left side) of fringe pattern to the other side (say, upto 3rd minima on right side). Plot the **Intensity vs. position of the detector** graph, in the Origin software. From the graph, determine the slit width (a) in case of single slit diffraction. Similarly, perform the measurements for double slit (replacing the single slit) experiment and determine the slit width (a) and the slit separation (d). Finally, estimate the error in the measurement of slit width (a) and slit separation (d).

Procedure for Single-slit /Double slit experiment:

A) Optical alignment

1. Set up the laser diode at one end of the optical bench and turn it on.
2. Place the Single-Slit Set (in its mount) on the optical bench in front of the laser source. Align the laser light and rotate the slit holder until the diffraction pattern produced by the slit is horizontal.
3. Adjust the alignment of the laser diode with the two thumbscrews on the back of the laser. You should adjust the vertical and horizontal alignment so that the laser beam is roughly centered on the slit in the Single-Slit Set.
4. Verify that the pinhole of the detector is set at the height of the diffraction pattern.
5. Make sure that the circular scale of the detector (i.e. the micrometer attached with the detector) is physically coupled (by a belt) with the pulley of the rotary motion sensor.

B) Preparation for data recording:

1. Connecting the *Science Workshop* interface to the computer:

(i)Connect the Rotary Motion Sensor cable to Digital Channels 1 and 2.

(ii) Connect the Light Sensor cable to Analog Channel A and then turn on the power.

2. Selecting of the Sensors and their relevant parameters: Click on the **Data studio software** for the experiment setup window.

(i)Select the **Rotary Motion Sensor** and connect it to **Channels 1** and **2**. Set up the Rotary Motion Sensor for <u>high resolution</u> (for example, 1440 Divisions per Rotation). Select <u>*Large Pulley (Groove)*</u> .

(ii)Select the **Light Sensor** and connect it to **Channel A**. Set the <u>sample rate to 50 Hz</u> and <u>low resolution</u>. Make sure that the <u>gain of the detector is set at 1</u>.

3. Selecting of the Display: Select a **Graph** display and then set the axes of the graph display so that **light intensity** is shown on the *vertical* axis and **angular position** (of the pulley) is on the *horizontal* axis.

C) Data recording:

1. Press **start** for recording the data.
2. Slowly move the detector by rotating the micrometer-screw of the detector. Continue to rotate the micrometer-screw until the detector reaches the other side of the diffraction pattern
3. After finishing the measurement, press **stop** recording data.
4. **Export** the data from **Data Studio software** and **save** it as '.dat' or '.text' file.
5. Plot the data in **Origin software** and convert the scale of x-axis from **angular position** (of the pulley) to **linear position** (of the detector in units of mm) by multiplying the conversion factor.
6. Conversion factor can be determined from the **Data Studio software** by measuring the **angular rotation** (of the pulley) corresponding to 1mm linear shift of the detector.