PHYS 201   LAB 01

Interference and Diffraction Using Visible Light

1. Objective

The objective of this experiment is to show that light can exhibit wavelike properties such as interference and diffraction.

2. Theory

NOTE: The theory used in this lab is covered in <u>Serway & Jewitt</u> "Principles Of Physics" Fourth Edition, Chapter 27: Wave Optics in sections 27.1-3 and 27.6 .

2.1 Introduction

If two or more waves of light of the same frequency overlap at some point in space the resulting effect produced depends both on the phases and amplitudes of the two waves. This phenomenon, called interference, can not be explained   on the basis of ray optics or the corpuscular nature of light – the wave nature of light must be explicitly invoked.

Two sources of light are called coherent if they emit light waves of the same frequency and the emitted waves have a constant phase relationship between them. Light radiating from coherent sources is also called coherent light. Thus light from such sources as a lightbulb, a candle or a star is incoherent. As described in your textbook, light waves are transverse waves. To observe interference on the laboratory time scale using light waves an additional condition must be imposed – the two interfering waves must have the same polarization. One way to produce such two coherent waves is to use radiation from two different parts of the same wavefront.

We will use the following notation for variables in this experiment:

> a = width of slit(s)
> d = distance between two slits in double-slit experiments
> y = position of light sensor relative to center of interference pattern
> θ = arctan(y / L) = diffraction angle of light at position y

The diffraction angles involved in this experiment are small enough that we will assume throughout that $\sin(\theta) = \tan(\theta) = \theta$. Therefore we can write simply $\theta = y / L$.
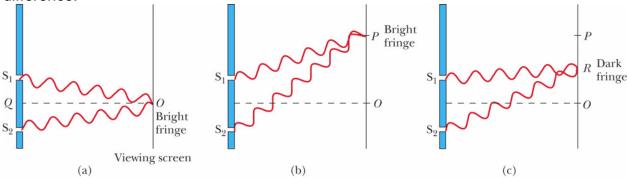
The following symbols indicate constants for the experiment:

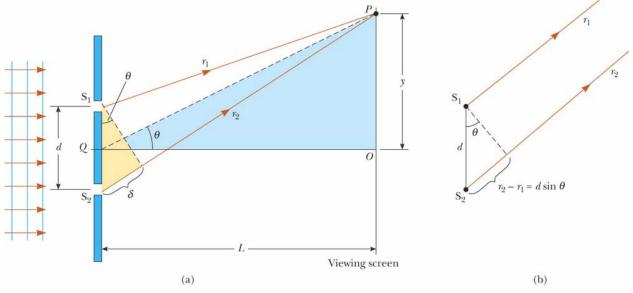> λ = wavelength of laser light = 650nm
> L = distance from slit(s) to light sensor = 80cm

2.2   Double-Slit Interference Theory

Consider two point sources S_1 and S_2 of coherent light as shown below. The light waves from each slit will spread out in all directions. At a particular point on the viewing screen, the light waves from the two slits will interfere in a way that depends on their phases difference.

(a)   (b)   (c)

If the two waves depicted in the diagram are **in phase** when they strike the target, we expect constructive interference to produce a bright fringe, where the intensity is maximum. If the two waves are out-of-phase, we expect a dark fringe, where the intensity is minimum. We can approximate the **path difference** between the two waves with the geometric construction shown below:

(a)   (b)

If L is much larger than d, then geometrically, we can approximate that $\delta \approx d \sin(\theta)$. For a particular angle θ, we expect constructive interference to produce an intensity maximum if the path difference δ is an integer multiple of λ. By the same reasoning, we expect minima to occur when δ is a half-integer multiple of λ.   Therefore we expect bright and dark fringes to occur at the following angles:

$$\sin \theta_{bright} = n\,\frac{\lambda}{d} \qquad\qquad \sin \theta_{dark} = \left(n + \frac{1}{2}\right)\frac{\lambda}{d}$$
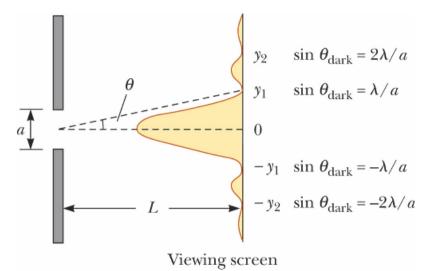
Here we are using n as a label for keeping track of the different maxima and minima. Using the small-angle approximation $\sin \theta = \tan \theta = y / L$ and our known values for L and λ we have the following approximate formula for minima:

$$y = \left(n + \frac{1}{2}\right)\frac{L\lambda}{d} = \left(n + \frac{1}{2}\right)\frac{(80 \cdot 10^{-2})(650 \cdot 10^{-9})}{d}$$

2.3 Single-Slit Theory

Of course, each slit has a finite width and thus is not really a "point" source of light . By the same reasoning we used for double-slit interference, light waves passing through different parts of a single slit travel slightly different distances to the target. Thus light from a single slit can interfere with itself! This self-interference is called **diffraction**.

To calculate the effects of diffraction, we use Huygens' principle: each point inside the slit can be modeled as a point source of light. We then add together the effects of all the points (or rather, integrate them - there are infinitely many points) to find a formula for the single-slit interference pattern. If $L \gg a$, the result is a **Fraunhofer pattern**:

$$y_2 \qquad \sin \theta_{dark} = 2\lambda/a$$
$$y_1 \qquad \sin \theta_{dark} = \lambda/a$$
$$0$$
$$-y_1 \quad \sin \theta_{dark} = -\lambda/a$$
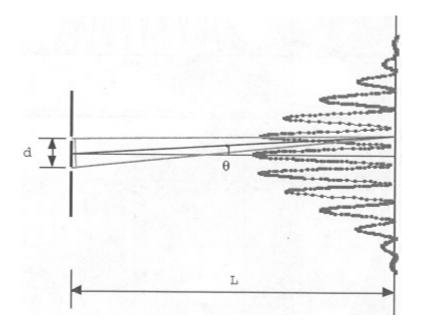$$-y_2 \quad \sin \theta_{dark} = -2\lambda/a$$

Viewing screen

Instead of calculating the actual Fraunhofer pattern, we need only approximate the locations of its first few minima for our purposes. If we model the light passing through the slit as two point sources a distance $a/2$ apart, then the double-slit interference formula tells us the first minimum occurs when $(a/2) \sin(\theta) = \lambda/2$. Modelling the light as four point sources each a distance $a/4$ apart gives $(a/4) \sin(\theta) = \lambda/2$, and so on for 8,

$$\sin\theta = m\frac{\lambda}{a}$$

16, 32, etc. point sources. Therefore if m is any nonzero integer, we can write:
This derivation was not very rigorous, but this formula does gives the location of single-slit intensity minima in the limit that L is much larger than a. Again using the small-angle approximation and plugging in the known values of L and λ, we have:

$$y = m\frac{L\lambda}{a} = m\frac{(80 \cdot 10^{-2})(650 \cdot 10^{-9})}{a}$$

In the double-slit experiments, both effects will be at work: diffraction of light through each slit and interference from the two separate slits. The observed double-slit pattern will have minima corresponding to *both* formulas, and the pattern itself will look like this:

The Fraunhofer pattern formed by diffraction at each slit acts as an "envelope" which limits the amplitude of the intensity fringes formed by double-slit interference.

3. Experimental Details

The experiment is divided into two parts:

In **Part 1 (Single Slit Diffraction)**, we shine laser light through a single slit and analyze the resulting diffraction pattern on a target behind the slit. This is done for two

slits of different sizes. In **Part II (Two-Slit Interference)**, we shine light through two identical slits and analyze the resulting interference pattern. The distance between slits is varied to observe changes in the interference pattern. Below is the summary of the two experiments and their corresponding parameters.

Summary of Experimental Parameters

Part I – Single Slit Diffraction

$a = 0.16$ mm
$a = 0.08$ mm

Part II – Double Slit Interference

$a = 0.04$ mm, $d = 0.25$ mm
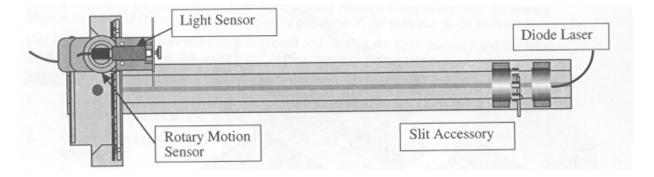$a = 0.04$ mm, $d = 0.50$ mm

BEFORE YOU BEGIN: IMPORTANT PRECAUTIONS

 - Do not look directly at the laser. Doing so may lead to permanent damage to your eyes.

 - Handle the linear translator / light sensor assembly with care.

3.1 Apparatus

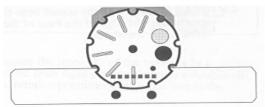The apparatus consists of the following components, as viewed from above:

The light sensor and rotary motion sensor are mounted on a rack assembly called the Linear Translator. The concept is simple: a laser shines onto one or more slits and the resulting light strikes a target 80cm away, forming a horizontal interference pattern.

Before starting the experiments, run through the following checklist:

1. Turn on the laser. (There is a switch on the back.)

2. There are two different Slit Accessories marked **Single Slit Set** and **Multiple Slit Set**. Check the **Single Slit Set** is in use. Look at the Slit Accessory from above and ensure that the disk lines up approximately with the **20cm** mark on the metal rail.

3. Turn the Slit Accessory disk so that the laser light passes through the **0.16mm** slit. If the laser is not aimed at the slit, use the adjustment knobs on the laser to re-aim it.

4. The laser light should strike the Aperture Bracket, which looks like this:

The light pattern should be horizontal and pass through the aperture to reach the light sensor. If it does not, use the adjustment knobs to fine-tune the laser's aim. Rotate the wheel to select aperture size setting **#2** if it is not already in this position.

5. Check that the white plastic screen on the aperture is approximately lined up with the **100cm** mark on the metal rail, as viewed from above.

3.2 Setting up the DataStudio software

Log in to the computer and double-click the **Physics Experiment Resources** folder, then **Interference and Diffraction of Light** and **DataStudio Files**. Double-click the file **Diffraction.ds** to open the DataStudio activity.

Check the **Experiment Setup** window. You should see a picture of the ScienceWorkshop 750 USB interface box. (Be sure that the box is switched on!) If the "Click To Connect" icon appears, click it. There should be icons for the light sensor and rotary motion sensors indicating that both sensors are connected.

Click on the **Diffraction and Interference** window to bring it to the front. Select **Monitor Data** in the **Experiment** pull-down menu (or press Command-M) to start Monitor Mode. In this mode, DataStudio will display data on screen without recording.

Gently move the light sensor assembly back and forth along the Linear Translator rack. It is important to move the assembly smoothly and slowly: it should take you about 30-60 seconds to move the light sensor across the entire visible range of the interference pattern. It is not necessary to move the assembly at a constant speed. (You may want to lean the back of the assembly against the metal rail underneath it to prevent the light sensor from tipping forwards, which can affect the accuracy of the experiment.)
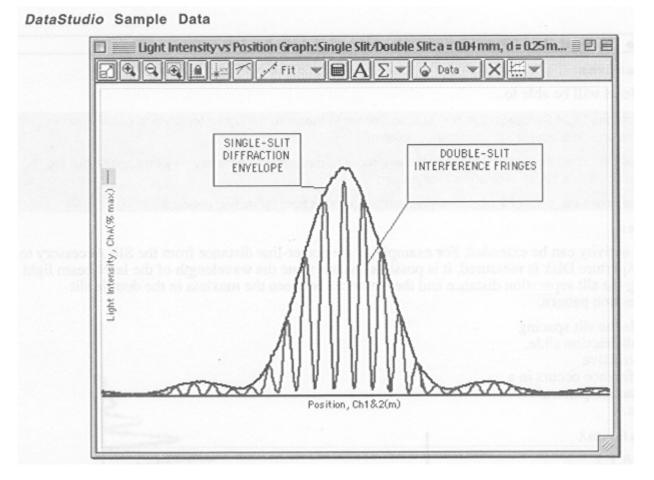
If DataStudio is set up properly, you will see data points appear on-screen forming a

graph of light intensity vs. position. To exit Monitor Mode, click the **Stop** button at the top of the screen. Clicking the **Start** button will begin data recording (don't do this yet).

3.3 Recording Data

Move the sensor assembly so that it rests against the black clamp on the Linear Translator rack. Remember to do this before each experiment or the graphs from different experiments will not line up correctly. (DataStudio always defines 0cm to be the location of the sensor assembly when you first pressed the **Start** button.)

Click the **Start** button and move the sensor assembly across the entire visible interference pattern. Click **Stop** when you are finished. If there is a problem during data recording, you can select **Delete Last Data Run** from the **Experiment** menu (or press Command-minus), click **OK**, and start again.

DataStudio Sample Data

The screenshot above shows a typical DataStudio window with two data sets superimposed: a single-slit data set with a = 0.04mm and a double-slit data set with a = 0.04mm and d = 0.25mm. The icons at the top will be used later for analysis.

Once you are satisfied with your data, repeat the experiment with the following settings. (Use the Double Slit Set accessory for the third and fourth experiments.)

Single Slit: *a=0.16mm*

Single Slit: a=0.08mm

Double Slit: *a* = 0.04mm   *d* = 0.25mm

Double Slit: *a* = 0.04mm   *d* = 0.50mm

3.4 Analyzing Data

The **Diffraction and Interference** window will show the results of the most recently recorded data. To view all of the data at once, use the **Single-Double Comparison** window. Click the **Data** box in the toolbar at the top of the window to select which data recordings should be displayed in the window.

Click the **Scale to fit** icon at the top left of either window to automatically re-size the displayed data. To zoom in on a particular section of the data, use the **Zoom Select** icon (a magnifying glass with a + and a dotted rectangle). Click and drag to draw a box and DataStudio will zoom in on that box.

To find the coordinates of an individual data point, click the **Smart Tool** icon (the letters *xy* with two perpendicular dashed lines.) Click on the center of the Smart Tool and drag it to a data point to see that point's coordinates.

We are interested in the locations of the local intensity minima of the interference pattern. To find these, drag the **Smart Tool** to each minimum value. The location will be displayed as an x-coordinate on the graph. Write these down on the data sheet. The **Zoom In** and **Zoom Out** tools may be useful for finding minima more precisely.

To keep track of the different minima, we label each with an **order number**. Minima caused by single-slit diffraction have been labeled **m** and double-slit interference minima have been labeled **n**. The different minima are labeled on the data sheet in the order that they appear as the Smart Tool is moved away from the center of the pattern.

Note that DataStudio defines 0cm to be the starting position of the motion sensor, while our theoretical predictions define 0cm as the center of the interference pattern. To correct for this, write down each minimum left of center in the **L** column and each corresponding mirror-image in the **R** column. Then calculate the distance (**R** - **L**) / 2 from each minimum to the midpoint between them.

The single- and double-slit experiments are (hopefully!) unchanged if the sign of *y* is reversed. Therefore we expect every minimum at *y* to have a "mirror-image" at -*y*.
If this is indeed a symmetry of the experiment, then the minimum-to-midpoint distances (**R** - **L**) / 2 should be the same regardless of where we define 0cm to be.

3.5 Evaluating Error

The error in each measurment is defined to be (**measured** - **predicted**) / **predicted** . For each order number, record the error calculated this way in the last column.

For example, suppose the **m** = 1 minimum is predicted to occur 0.650 cm from center. Suppose the measured left and right minima occur at 3.671 cm and 4.995 cm . Then the measured (**R** - **L**) / 2 distance is (4.995 - 3.671) / 2 = 0.662 cm . The error for this measurement is (0.662 - 0.650) / 0.650 = 0.019 = +1.9% .

3.6 Just for Fun!

The Single Slit Set includes a black screen with a square hole of side *s*. Before shining the laser onto this screen, discuss with each other what pattern will result. Sketch a picture of the pattern you predict. Then shine the laser through this square and observe the resulting pattern. Sketch a picture of the pattern you observe and explain it using what you have learned in this lab.