# XI. INTERFERENCE AND DIFFRACTION OF LIGHT *f04.01*

## INTRODUCTION

Light is a form of electromagnetic waves. Waves move differently than particles. Waves diffract (deflect in various directions) when passing through a narrow opening, while particles continue along a straight line. Interference of waves plays an important role in explaining diffraction patterns.

## PURPOSE

Observation of light interference and diffraction patterns.

## PRE-LAB ASSIGNMENTS

### A. Readings:

Interference and diffraction is exhibited by all types of waves - sound waves, waves on water, electromagnetic waves, etc. In this lab you will observe and investigate interference and diffraction patterns using visible light. Visible light, as you may recall, is a particular type of electromagnetic wave. We begin by defining a few terms that frequently arise while studying diffraction-related phenomena.

**Monochromatic beam of light:** A monochromatic beam of light is a beam of light of a single wavelength (or color).

**Coherent sources (or waves):** Two or more sources are called coherent sources if the waves that leave the two sources bear a definite relationship to each other. If the two waves do not bear a definite relationship to each other then they are said to be incoherent. Figure 1 is a sketch of two coherent sources. The difference between phases of the swings of each wave is constant in time and space. The waves do not need to be continuous. However, if the wave has a discontinuity, the other wave must change in exactly the same wave. Figure 2 is a sketch of two incoherent sources. The waves have discontinuities at different points, thus the phase difference changes. If waves have different wavelengths then they are incoherent since the phase difference changes continuously.

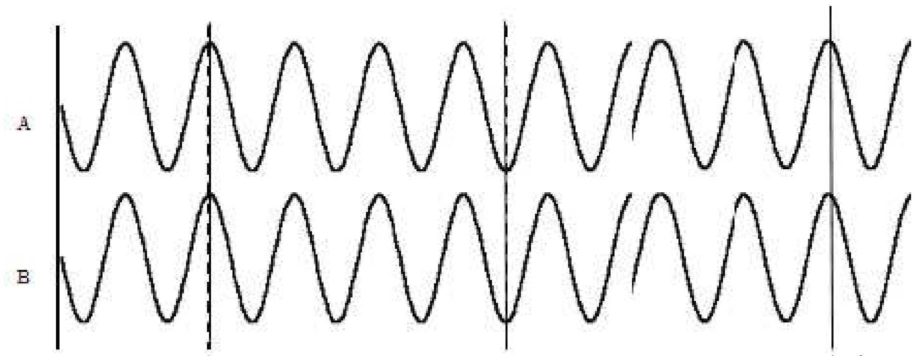


Figure 1. The figure shows waves emitted by two coherent sources A & B. The waves are coherent because the phase difference between the two waves is always the same.
The example shown here is a special case, since these two waves are exactly in phase: the crests of waves emitted by source A always corresponds to the crests of the waves emitted by source B and similarly for the troughs. The waves don't need to be exactly in phase to be coherent. For example, the crest of one wave can coincide with troughs of the other one (exactly out of phase), or any case in between these two extremes.

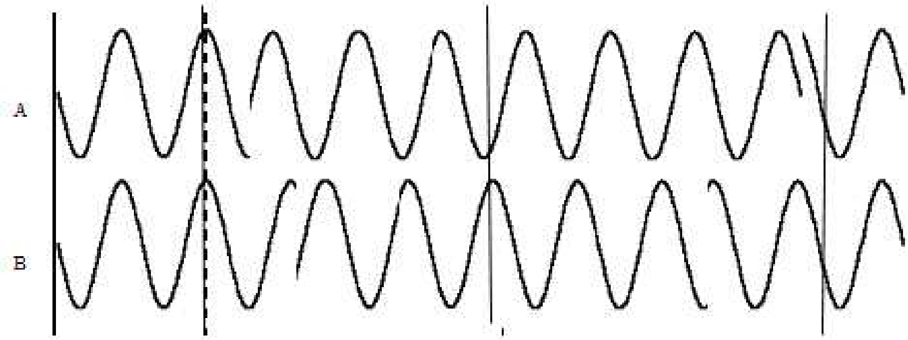


Figure 2. The figure shows waves emitted by two incoherent sources A & B. The waves are incoherent because the phase difference between the two waves changes.

**Waves exactly in phase and exactly out of phase:** Two coherent waves are said to be exactly in phase if a crest (trough) of one wave exactly coincides with the crest (trough) of the other wave. The two waves shown in Figure 1 are exactly in phase with respect to each other. Two waves are said to be exactly out of phase if a crest (trough) of one wave exactly coincides with the trough (crest) of the other wave.

**Constructive and destructive interference:** When one wave encounters the other they simply add and create one resultant wave. When two waves having the same amplitude and wavelength and exactly in phase with respect to each other interfere with one another the amplitude of the resulting wave is twice the amplitude of the individual waves and the two waves are said to undergo constructive interference. Similarly, when two waves with the same amplitude and wavelength and exactly out of phase with respect to each other interfere with one another the amplitude of the resulting wave is zero and the two waves are said to undergo destructive interference. Source of waves must be coherent to create a stable interference pattern.

**Waves passing through a narrow slit.** When a plane wave encounters a barrier with a narrow opening, it bends and spreads out as a circular wave as it passes through the opening (Figure 3a). On the other hand a parallel beam of particles while passing through a narrow opening do not spread out (Figure 3b).

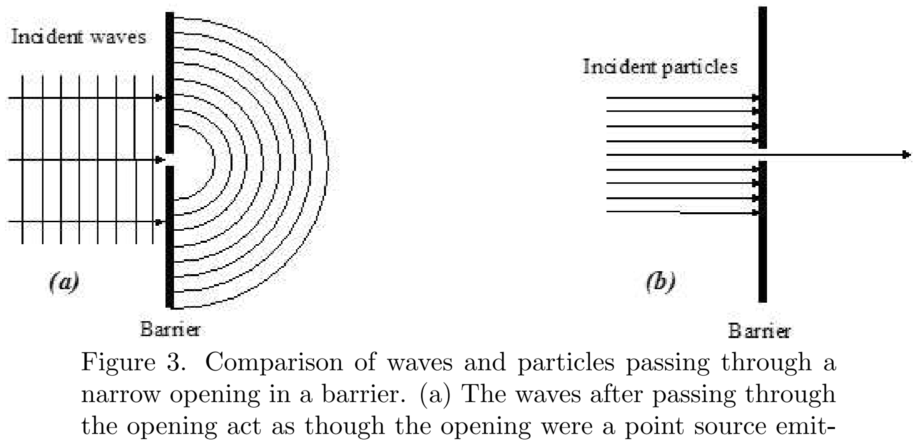


Figure 3. Comparison of waves and particles passing through a narrow opening in a barrier. (a) The waves after passing through the opening act as though the opening were a point source emitting circular waves. (b) Particles pass through the opening unobstracted - they continue along the straight line.

**Double-slit interference pattern.** Consider a parallel, monochromatic beam of light (for example light from a laser beam) incident on a barrier that consists of two closely spaced narrow slits S1 and S2. The narrow slits split the incident beam into two coherent beams of light. After passing through the slits the two beams spread out in all directions. They overlap each other, hence interfere (Figure 4a). If this transmitted light is made to fall on a screen some distance away one observes an interference pattern of bright and dark fringes on the screen (depicted in Figure 4b and Figure 4c). The bright fringes correspond to regions where the light intensity is a maximum (constructive interference) and the dark fringes correspond to regions where the intensity is a minimum (destructive interference).

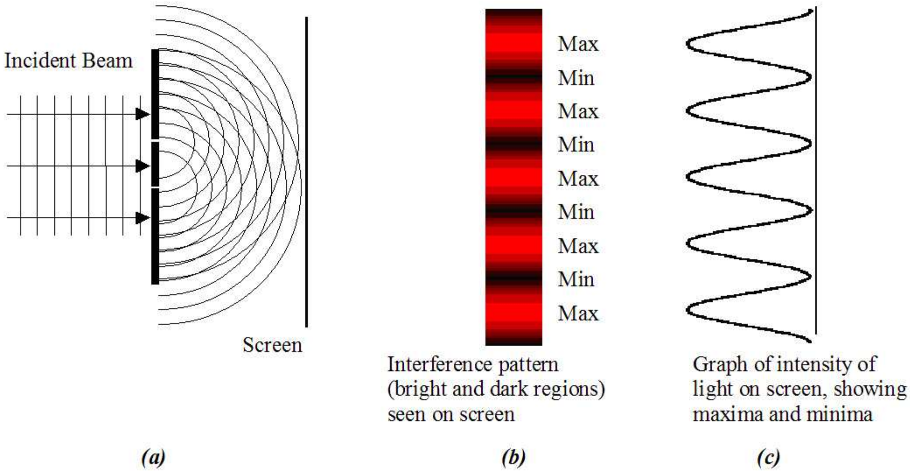


Figure 4. (a) The experimental setup to observe a double-slit interference pattern, (b) The interference pattern observed on the screen showing the bright and dark fringes, and (c) a sketch of the intensity maxima and minima.

How is this interference pattern produced? Let us try and understand the bright fringe located at the center of the screen between the two slits.

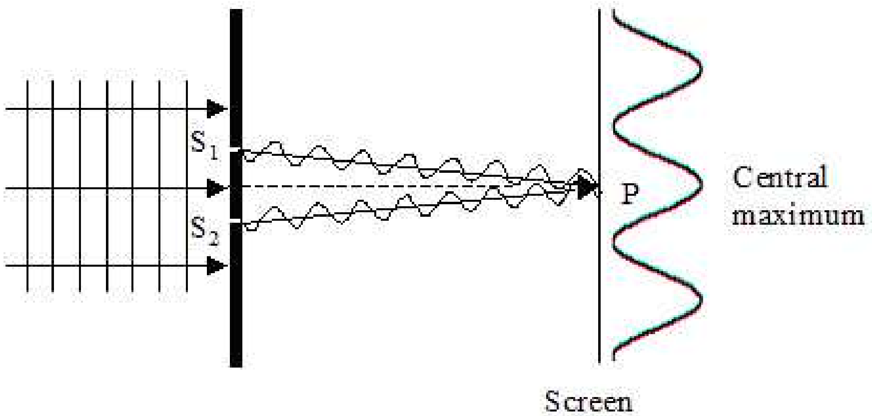


Figure 5. The waves reaching the point P at the center of the screen are exactly in phase since they travel equal distances.

Figure 5 shows the waves reaching the point P from the slits S1 and S2. The waves emerging from the slits S1 and S2 are exactly in phase. Since they travel the same distance to reach the point P they are in phase at the point P. In other words a crest of one wave arrives at the same time as a crest from the other wave. The two waves therefore interfere constructively at the point P and hence there is a bright fringe (or a maximum) at the center of the screen. To explain how the other bright fringes seen on either side of the central maximum are produced refer to Figure 6. Let $\lambda$ be the wavelength of the incident light. Let $d$ be the distance between the two slits and $L$ be the distance from the slits to the screen. Suppose the point P1 corresponds to the position of the first maximum above the central bright fringe.

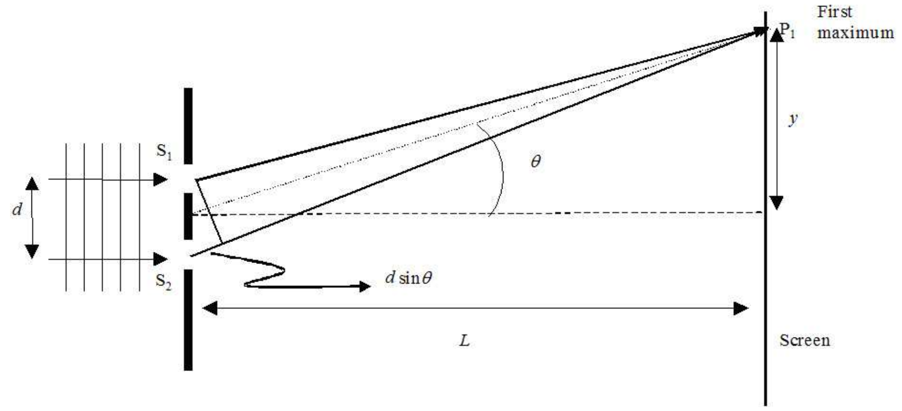


Figure 6. The wave reaching point P1 from slit S2 must travel an extra distance $d\sin\theta$.

From Figure 6 it is clear that the line from S2 is greater than the line from S1 which means that the wave from S2 travels an extra distance to reach point P1. If we assume that the slit-to-screen length $L$ is much greater than the slit separation $d$ ($L \gg d$) then the lines from the two slits to the point P1 are approximately parallel and the excess distance traveled by the wave from S2 or the path difference is approximately $d\sin\theta$.

Since the two waves interfere constructively at point P1, the two waves reaching point P1 must be exactly in phase and hence the path difference must be equal to one wavelength. i.e.,

$$d\sin\theta = \lambda \tag{1}$$

Equation (1) is also responsible for the presence of the first bright fringe below the central maximum. In general, for all points on the screen where the path difference is some integer multiple of the wavelength the two waves from the slits S1 and S2 arrive in phase and bright fringes are observed. Thus the condition for producing bright fringes is

$$d\sin\theta = \lambda, 2\lambda, 3\lambda, 4\lambda, .... \tag{2}$$

Similarly, dark fringes are produced on the screen if the two waves arriving on the screen from slits S1 and S2 are exactly out of phase. This happens if the path difference between the two waves is an odd integer multiple of half-wavelengths. i.e.,

$$d\sin\theta = \lambda\,1/2, \lambda\,3/2, \lambda\,5/2, \lambda\,7/2, .... \tag{3}$$

If $y$ is the distance of a given bright or dark fringe from the central maximum on the screen (Figure 7) then

$$\tan\theta = \frac{y}{L} \tag{4}$$

Our assumption $L \gg d$ implies that the angle $\theta$ is very small and hence

$$\sin\theta \approx \tan\theta = \frac{y}{L} \tag{5}$$

Equations (2), (3) and (5) imply that the interference maxima (bright fringes) are located at

$$y = 0, \lambda\frac{L}{d}, 2\lambda\frac{L}{d}, 3\lambda\frac{L}{d}, ... \tag{6}$$

on the screen, while the interference minima (dark fringes) are located at

$$y = \frac{1}{2}\lambda\frac{L}{d}, \frac{3}{2}\lambda\frac{L}{d}, \frac{5}{2}\lambda\frac{L}{d}, ... \tag{7}$$

on the screen. Thus, the distance between adjacent maxima or adjacent minima on the screen is

$$\Delta y = \lambda\frac{L}{d} \tag{8}$$

**Diffraction pattern from a single-slit of finite width.** Consider a beam of light incident on a barrier consisting of a single slit of width $a$. Situation depicted in Figure 3a applies only to a very narrow (point-like) slit, in which $a$ is very small compared to the light wavelength, $a \ll \lambda$. Now we will consider a slit of finite width.

If the light passing through the slit is made to fall on a screen a distance $L$ away from the slit, one observes, so called **diffraction pattern** of alternating dark and bright fringes on the screen (Figure 7).

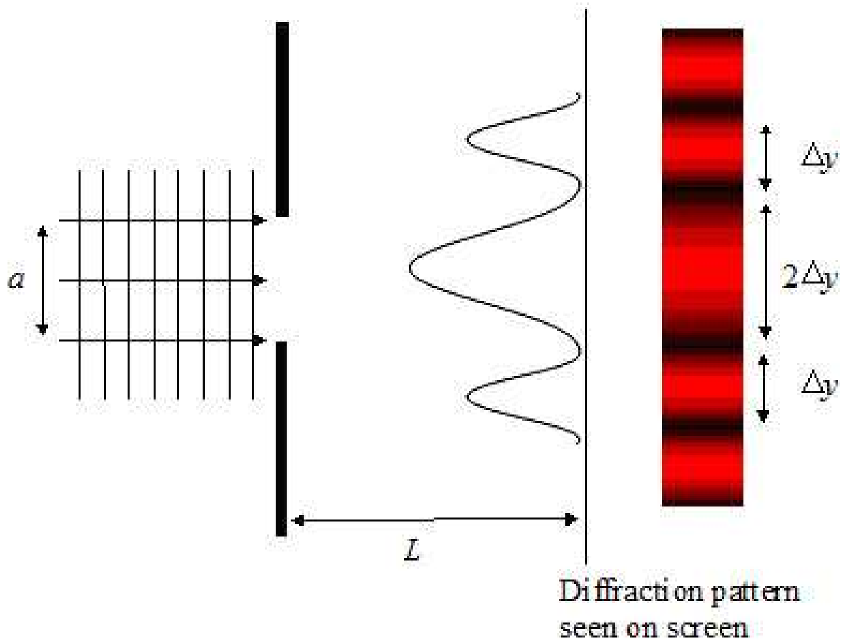


Figure 7. Single-slit diffraction pattern.

The diffraction pattern produced on the screen can be explained by assuming that each point on the wave passing through the slit acts as a source of circular waves and emits light in the forward direction. These waves interfere with one another resulting in the dark and bright fringes observed on the screen. Therefore, diffraction is a special case of light interference.

An argument not unlike the one presented while discussing the double-slit interference pattern shows that the spacing between the dark fringes on the screen is given by

$$\Delta y = \lambda \frac{L}{a} \tag{9}$$

except for the dark fringes on either side of the central maximum which are a distance $2\Delta y$ apart (refer to Figure 7). Notice the central maximum in a single-slit diffraction pattern has a width $2\Delta y$.

In case the slit is very narrow, $\lambda \gg a$, the separation of the fringes is very large. A point-like slit corresponds to $a \to 0$. In that case $\Delta y \to \infty$. Thus, the central maximum becomes infinitely broad. This is the case of circular wave depicted in Figure 3a.

It is also interesting to consider the slit which is very broad, $\lambda \ll a$. In the limit of very broad slit, $a \to \infty$, the separation between fringes becomes infinitely small, $\Delta y \to 0$. In other words all fringes appear at the same place, or simply all light is incident at the center of the screen. But this is how particles move! No light was deflected. When all obstacles are large compared to the wavelength, the light travels along the straight lines. This is the case of so called **geometrical optics**. In case the light interacts with objects of dimensions comparable to the wavelength we talk about **wave optics**.

### B. Exercises:

Please answer the questions on Report Sheet XI–1, which will be collected at the *beginning* of the laboratory session and graded by your instructor.

**REPORT SHEET XI–1**

Date______________________ Name______________________

Instructor______________________

PRE-LAB EXERCISES

**Exercise 1.**
Does an ordinary light bulb emit monochromatic light? Explain.

**Exercise 2.**
A laser beam of wavelength $650 \times 10^{-9}$ meter is incident on a double-slit with a slit separation of 0.125 mm. An interference pattern is produced a distance 1.5 m away from the slits. What is the distance between adjacent dark fringes? Show your calculation.

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## LABORATORY ASSIGNMENTS

**Materials Needed:**

- Red laser (PASCO OS-8528 Diode Laser)
- PASCO OS-8529 Slit Accessories (Multiple Slit Set and Single Slit Set)
- Optical bench
- Wood board fixed to the table to be used as a screen
- Sheet of paper mounted on the wood board. Graph paper recommended.
- Ruler if you don't use graph paper (metric with length 30 cm)
- Meter stick (at least 1.0 m long)
- Desk lamp or flashlight

## Experiment A: *Getting familiar with the equipment and the initial setup.*

### Procedures

**A-1.** At your table you will see a laser beam mounted on an optics bench, a pair of slit accessories and a wooden board clamped firmly on one end of the table that will act as a screen.

**A-2.** Ensure that the optics bench is approximately perpendicular to the wood board, as shown in Figure 8.

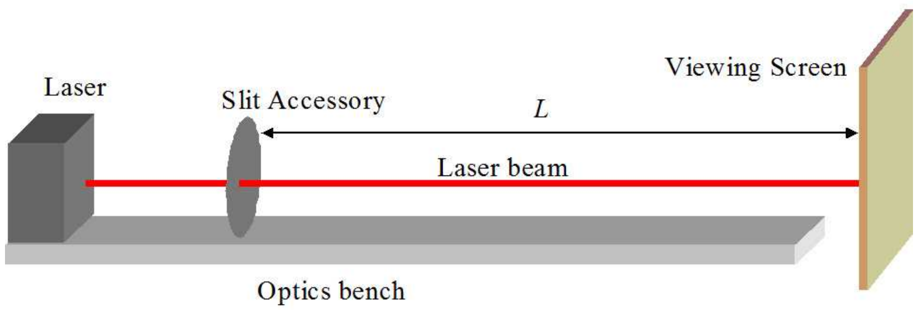


Figure 8. *Experimental setup.*

**A-3.** On your table you will find a pair of slit accessories - two plastic circular disks with apertures mounted on metal frames.

One of them is the MULTIPLE SLIT SET which consists of various types of double-slits (see Figure below) and the other is the SINGLE SLIT SET which consists of various single-slits and apertures of other shapes.

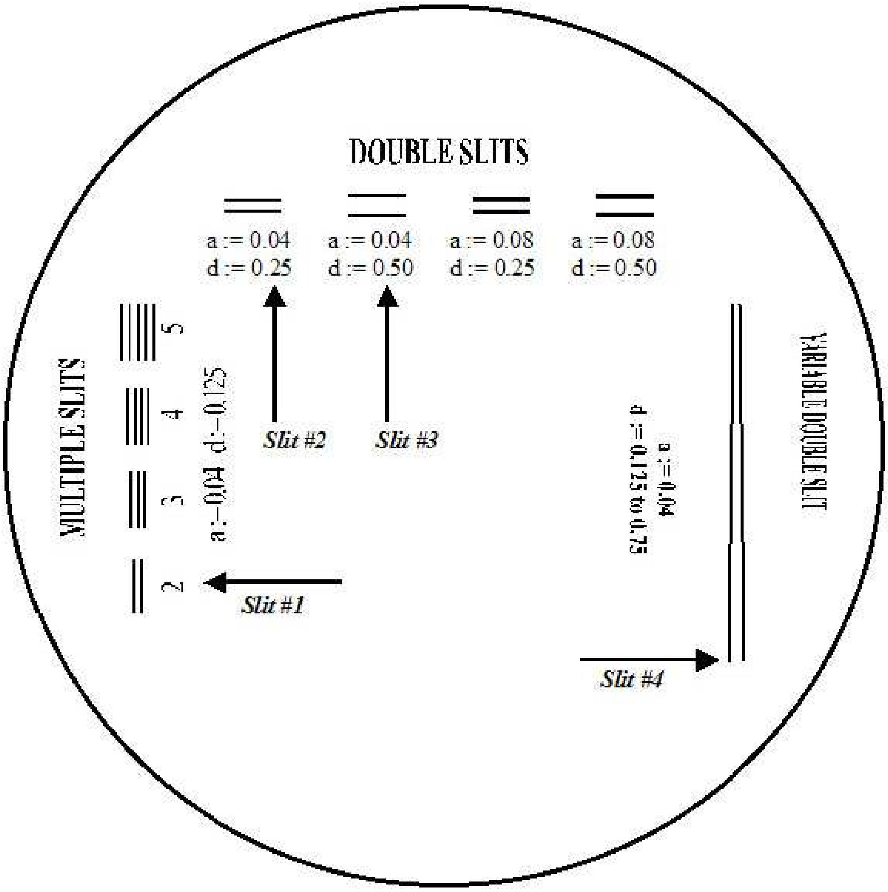


Figure 9. The locations of the slits on the Pasco Multiple Slit Set (the true distribution of slits is circular). The four double-slits needed for Activities A and B are marked Slit #1, Slit #2, Slit #3, and Slit #4. The values of $a$ and $d$ are in millimeters.

**A-4.** Look carefully at all the slits that you see on the MULTIPLE SLIT SET. It contains slits classified as DOUBLE SLITS, a VARIABLE DOUBLE SLIT, COMPARISONS and MULTIPLE SLITS.

Each double-slit on the MULTIPLE SLIT SET is characterized by two numbers - $a$ and $d$. The number $a$ represents the width of each slit (slit width) while the number $d$ is the distance between the two slits (slit separation).

All distances mentioned on the both slit accessories are measured in millimeters.

**A-5.** Identify the following four double-slits on the MULTIPLE SLIT SET. Referring to Figure 9 may be helpful.

In the slits under MULTIPLE SLITS identify the only double-slit (it has a 2 written below it). This double slit has dimensions

$$a = 0.04mm, \quad d = 0.125mm \qquad (Slit\#1)$$

In the slits under DOUBLE SLITS identify the double-slits with dimensions

$$a = 0.04mm, \quad d = 0.25mm \qquad (Slit\#2)$$

$$a = 0.04mm, \quad d = 0.5mm \qquad (Slit\#3)$$

The fourth double-slit is actually the end of the VARIABLE DOUBLE SLIT with the largest slit separation. This corresponds to a double-slit with dimensions

$$a = 0.04mm, \quad d = 0.75mm \qquad (Slit\#4)$$

**A-6.** *The laser beam safety:* AVOID LOOKING DIRECTLY INTO THE LASER BEAM OR THE REFLECTION OF THE BEAM FROM A MIRROR OR METAL SURFACE. Place the laser at the end of the optics bench furthest from the wood board. Switch the laser ON and you should see a bright red spot on the wooden board.

**A-7.** Place the MULTIPLE SLIT SET on the optics bench about 10 cm - 15 cm (100 mm - 150 mm) in front of the laser beam with the dark plastic surface facing the laser beam.

Arrange the equipment so that the distance $L$ between the MULTIPLE SLIT SET and the wood board is exactly 1.5 m. You must maintain this distance unchanged for the entire lab.

Rotate the circular plastic disk so that the laser beam passes through the double-slit with $a = 0.04$ mm and $d = 0.125$ mm.

Adjust the two alignment screws on the back of the laser to direct the laser beam through the slit and maximize brightness of the image on the screen.

If your arrangement is correct, you will observe an interference pattern on the wood board. The interference pattern consists of closely spaced bright and dark fringes. You may have to get close to the wooden board to see this pattern.

Consult your instructor if you are not sure you have set things up correctly.

## Experiment B: *Double-slit interference pattern.*

### The Task:

Determining the wavelength of the laser beam from the double-slit interference pattern.

### Procedures

**B-1.** Obtain interference pattern from Double-Slit#1 ($a = 0.04$ mm, $d = 0.125$ mm) following the procedure described in Activity A.

Tape a sheet of paper to the wood board, so that the entire interference pattern falls on the sheet.

Notice that the bright and dark fringes in the interference pattern are evenly spaced.

**B-2.** You need to determine the average distance between adjacent dark fringes. Here is one method of doing this accurately:

- Use a pencil to mark out the position of several (10 to 12, if possible) dark fringes on the sheet of paper by making a thin vertical line at the center of each dark spot.
- Remove the sheet of paper and measure the distance from the first mark to the last mark with a ruler, or use markings on the graph paper. It you use graph paper make sure it is metric or make conversion from inches to meters (e.g. "20 Squares to the Inch" means that the distance between thin lines on the paper are $1\ in./20 = 25.4mm/20 = 1.27mm = 1.27 \times 10^{-3}m$).
- Count the number of bright fringes enclosed by the first and last marks on the sheet of paper.
- Divide the total distance measured between the first and the last mark by the total number of bright fringes counted. This is the average distance $\Delta y$ between adjacent dark fringes. Record your measurements in Table in Report Sheet XI–1.

**B-3.** Repeat steps described in B-2 for the double-slit with $a = 0.04$ mm and $d = 0.25$ mm (Slit #2).

**B-4.** Repeat steps described in B-2 for the double-slit with $a = 0.04$ mm and $d = 0.5$ mm (Slit #3).

**B-5.** Repeat steps described in B-2 for the double-slit with $a = 0.04$ mm and $d = 0.75$ mm (Slit #4). This double-slit corresponds to the end of the VARIABLE DOUBLE SLIT with the largest slit separation.

**B-6.** From the equation (8) derived in the introduction:

$$\lambda = \Delta y \frac{d}{L} \tag{10}$$

Using this formula determine the light wavelength from the measurements for each slit. Express you results first in $m$ then in $nm$ ($1\,nm = 10^{-9}m$). Keep 3 significant digits.

**B-7.** Calculate average of your 4 determinations of $\lambda$ ($\lambda_{ave} = (\lambda_1 + \lambda_2 + \lambda_3 + \lambda_4)/4$). What is the largest deviation of the individual values from this average? Express it in percent:

$$\frac{\sigma_\lambda}{\lambda} = \frac{|\lambda_i - \lambda_{ave}|}{\lambda_{ave}} \times 100\% \tag{11}$$

The latter is a crude estimate of the accuracy of your measurements (measurement error).[1]

Report your results in Report Sheet XI–1.

[1] This is an estimate of so called *maximal error* made for each individual measurement. It is more common in error analysis to use so called *standard deviation.* Calculation of the standard deviation is more complicated, therefore we don't use it here. Accuracy of the average value is better than the accuracy of the individual measurements by a factor of $\sqrt{4} = 2$ (for 4 measurements).

**B-8.** Read the actual wavelength of the laser light from the laser casting ($\lambda_{actual}$) and copy it to Report Sheet XI–1. Calculate relative deviation (in percent) of the averaged measured wavelength from the actual one:

$$\frac{\delta\lambda}{\lambda} = \frac{|\lambda_{ave} - \lambda_{actual}|}{\lambda_{ave}} \times 100\% \tag{12}$$

Hopefully this deviation is within (or not much larger than) the accuracy ($\sigma_\lambda/\lambda$) of your measurements estimated in B-7.

## REPORT SHEET XI–2

Date______________________ Name______________________

Instructor______________________ Partner(s)______________________

**B-2,3,4,5,6**

| Double-slit dimensions (mm) | Distance between the first and the last mark (mm) | Number of fringes counted | Average $\Delta y$ (mm) | $\lambda$ | |
|---|---|---|---|---|---|
| | | | | (m) | (nm) |
| $a = 0.04$, $d = 0.125$ | | | | | |
| $a = 0.04$, $d = 0.250$ | | | | | |
| $a = 0.04$, $d = 0.500$ | | | | | |
| $a = 0.04$, $d = 0.750$ | | | | | |

**B-7.**

$$\lambda_{ave} = \qquad \text{nm}$$

$$\frac{\sigma_\lambda}{\lambda} = \qquad \%$$

**B-8.**

$$\lambda_{actual} = \qquad \text{nm}$$

$$\frac{\delta\lambda}{\lambda} = \qquad \%$$

blank

## **Experiment C:** *Single-slit diffraction pattern.*

**The Task:**

Determining the slit (or line) width from the diffraction pattern.

**Procedures**

**C-1.** Replace the MULTIPLE SLIT SET with the SINGLE SLIT SET.

Set the distance from the slit to the screen to be exactly 1.5 m.

Pass the laser beam through the single slit with slit width $a = 0.16$ mm. You should observe a diffraction pattern on the wood board.

Determine the average spacing $\Delta y$ between the dark fringes. Recall that in a single-slit diffraction pattern the width of the central maximum is twice the width of the other maxima. You must take this into account when calculating $\Delta y$. Refer to Figure 7.

Record the average spacing in Report Sheet XI–2.

**C-2.** Use equation (9), the actual wavelength of the laser and the average spacing between the dark fringes recorded in C-1 to determine the width of your single-slit. Show your calculation. Record your answer in Report Sheet XI–2.

**C-3.** Compare the value that you have calculated with the actual value ($a_{actual} = 0.16$ mm) by calculating the relative deviation in percent:

$$\frac{\delta a}{a} = \frac{a_{measured} - a_{actual}}{a_{actual}} \times 100\% \tag{13}$$

Record your answer in Report Sheet XI–2 and discuss it with your instructor,

**C-4.** Rotate the SINGLE SLIT SET to pass the light through $a = 0.08$ mm LINE (in LINE/SLIT part). Now the light passes through the set unobstracted except for the thin line in the center of the large square opening.

In wave optics it can be proven that diffraction on the line produces the same diffraction pattern as on the slit of the same width.

Determine the width of the line from your diffraction pattern following steps similar to C-1,2. Calculate relative deviation from the actual line width ($a_{actual} = 0.08$ mm).

Record your results in Report Sheet XI–2.

## **Experiment D:** *Diameter of a hair.*

**The Task:**

Determining the diameter of a hair using the diffraction pattern.

**Procedures**

**D-1.** The method described in the previous activity can be used to measure diameter of a thin wire or a hair.

Cut a small piece of your own hair. Mount it on the optical bench using a Scotch tape. Beam should be passing through the straight segment of the hair. Ask the instructor for help if you need suggestions how to accomplish this.

**D-2.** Measure the diameter (width) of the hair from the diffraction pattern, the same way as in the previous experiment. Record your results in Report Sheet XI–2.

**REPORT SHEET XI–3**

Date______________________ Name______________________

Instructor______________________ Partner(s)______________________

**C-1.** (slit)

$\Delta y =$ mm

**C-2.**
Write formula for $a$ in terms of $\Delta y$, $\lambda$ and $L$:

$a_{measured} =$ mm

**C-3.**

$\frac{\delta a}{a} =$ %

**C-4.** (line)

$\Delta y =$ mm $a_{measured} =$ mm

$\frac{\delta a}{a} =$ %

**D-2.** (hair)

$\Delta y =$ mm $a_{measured \quad 1} =$ mm

blank

## **Experiment E:** *Exploring interference patterns for various gratings.*

**The Task:**

Understanding structures of interference patterns created by diffraction gratings.

**Procedures**

**E-1.** A diffraction grating is a system of many obstacles of the same size and shape arranged in a regular pattern.

To explore transition from double-slit to diffraction grating use the MULTIPLE SLIT SET. Start from the double-slit which you used in Activity B-1 ("Slit #1"). Mark centers of the bright fringes (i.e. **maxima**) on the paper for a few brightest fringes.

**E-2.** Rotate the set by one position to increase the number of slits from 2 to 3 without changing their width or separation (go from the slits marked "2" to the slits marked "3" under MULTIPLE SLITS section - see Figure 8). Compare positions of the brightest maxima between the two patterns. You may notice additional faint maxima for the 3 slit pattern - ignore them. Then you can go to 4 and 5 slits put next to each other (rotate the set by two more positions).

Did separation of the brightest fringes (so called *principal maxima*) change?

How does the width of the brightest fringes change?

Use Report Sheet XI–3 to record your observations.

**E-3.** Now imagine having not 5 but many more slits of the same width and separation. This would be called line diffraction grating. The principal maxima will get even narrower.

**E-4.** We will now explore interference patterns created by light passing through gratings consisting of different apertures than a linear slit.

Mount SINGLE SLIT SET on the bench and pass the light through the grating consisting of many small SQUARES which can be found under PATTERNS section.

It may seem to you that this is just a single square opening. However, if you take it under a magnifying glass you will notice that this opening is filled with many small squares created by a wire mesh, as illustrated in Figure 10.

Try to sketch the central part of the pattern of the most intense interference maxima in Report Sheet XI–3. Measure distance between the centers of two neighbouring squares of the grating from the interference pattern you see. Indicate which distance you took for $\Delta y$ in your sketch.

**E-5.** Now switch to the HEXES pattern. This time the grating is made out of triangular wire mesh. Six triangles put together create a hexagon as outlined in the middle of Figure 10. Try to sketch the central part of the pattern of the most intense interference maxima in Report Sheet XI–3. Measure side of the trinagle in the wire mesh from the interference pattern you see. Indicate which distance you took for $\Delta y$ in your sketch.

**E-6.** Go to the next pattern called DOTS. This grating consists of many small dots. Try to sketch the central part of the pattern of fringes in Report Sheet XI–3. Measure distance between the dots from the interference pattern you see. Indicate which distance you took for $\Delta y$ in your sketch.

**E-7.** Finally use the pattern called HOLES consisting of many small, circular holes punched through the set. Try to sketch the central part of the pattern of fringes in Report Sheet XI–3. Measure distance between the centers of the holes from the interference pattern you see. Indicate which distance you took for $\Delta y$ in your sketch.

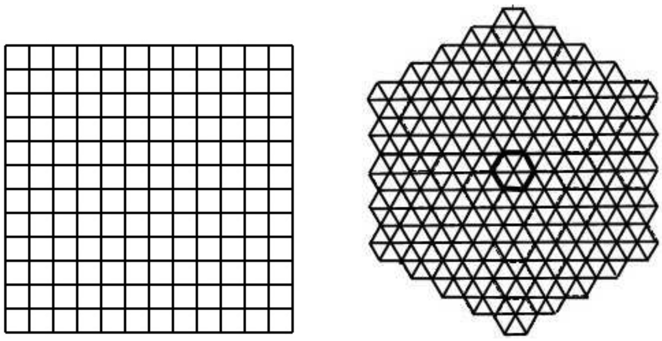

Figure 10. A magnified view of the SQUARES and HEXES patterns.

**E-8.** Switch the laser OFF.

## REPORT SHEET XI–4

Date____________________ Name____________________

Instructor____________________ Partner(s)____________________

**E-2.** MULTIPLE SLITS

Did separation of the brightest fringes (so called *principal maxima*) change?

How does the width of the brightest fringes change?

**E-4.** SQUARES

*(Sketch of the pattern)*

$\Delta y =$ mm

$d_{measured} =$ mm

**E-5.** HEXES

*(Sketch of the pattern)*

$\Delta y =$ mm

$d_{measured} =$ mm

**E-6.** DOTS

*(Sketch of the pattern)*

$\Delta y =$ mm

$d_{measured} =$ mm

**E-7.** HOLES

*(Sketch of the pattern)*

$\Delta y =$ mm

$d_{measured} =$ mm