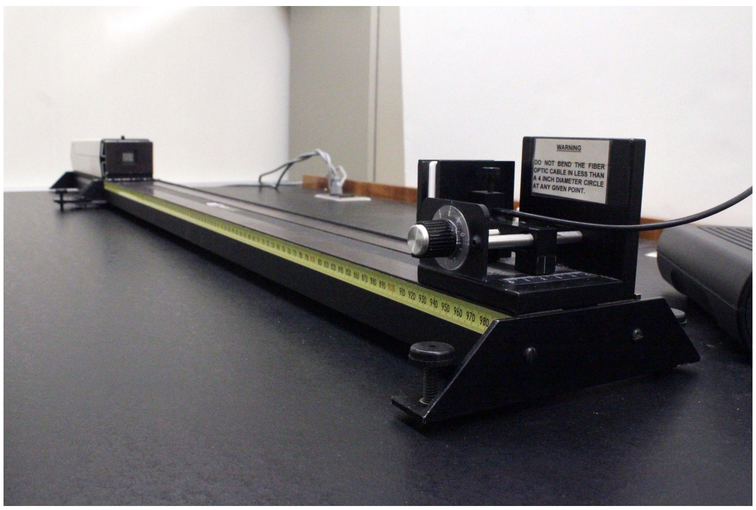
Physical Optics

APPARATUS

Shown in the picture below:

- Optics bench with laser alignment bench and component carriers
- Laser
- Linear translator with photometer apertures slide and fiber optic cable



Not shown in the picture above:

- Computer with ScienceWorkshop interface
- High sensitivity light sensor with extension cable
- Slit slides and polarizers
- Incandescent light source
- Tensor Lamp

INTRODUCTION

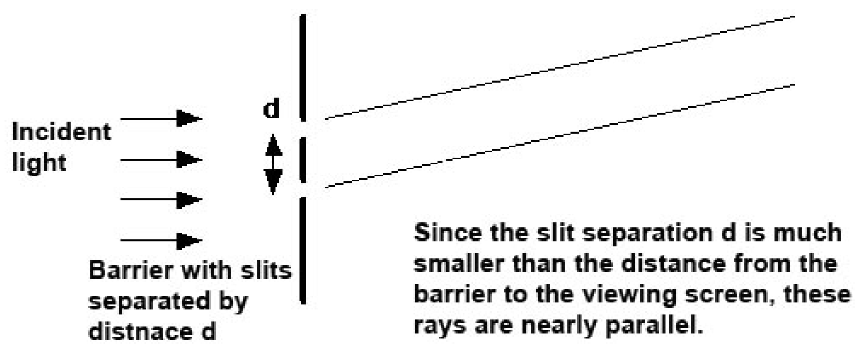
The objective of this experiment is to familiarize the student with some of the amazing characteristics of a laser, such as its coherence and small beam divergence. The laser will be used to investigate single- and double-slit diffraction and interference, as well as polarization. Furthermore, several interesting diffraction phenomena that are hard to see with standard light sources can be observed easily with the laser.

<u>WARNING: Do not look directly into the laser beam!</u> Permanent eye damage (a burned spot on the retina) may occur from exposure to the direct or reflected beam. The beam can be viewed without any concern when it is scattered from a diffuse surface such as a piece of paper. The laser beam is completely harmless to any piece of clothing or to any part of the body except the eye.

It is a wise precaution to keep your head well above the laser-beam height at all times to avoid accidental exposure to your own or your fellow students' beams. Do not insert any reflective surface into the beam except as directed in the instructions or as authorized by your TA. The laser contains a high-voltage power supply. Caution must be used if an opening is found in the case to avoid contacting the high voltage. Report any problems to your TA.

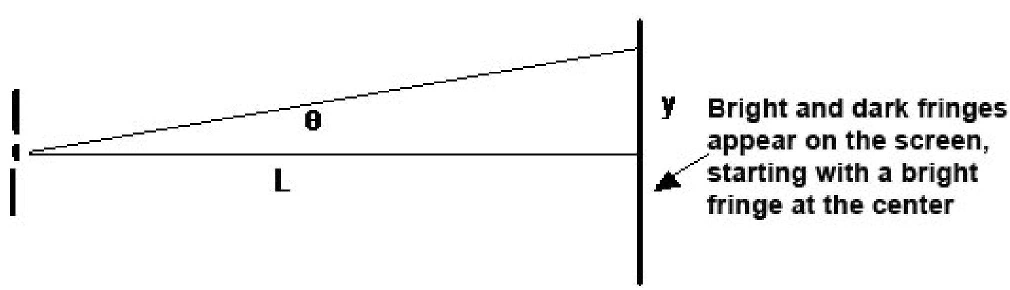
DOUBLE-SLIT INTERFERENCE

In the first part of the experiment, we will measure the positions of the double-slit interference minima. Schematically, a double-slit setup looks as follows:

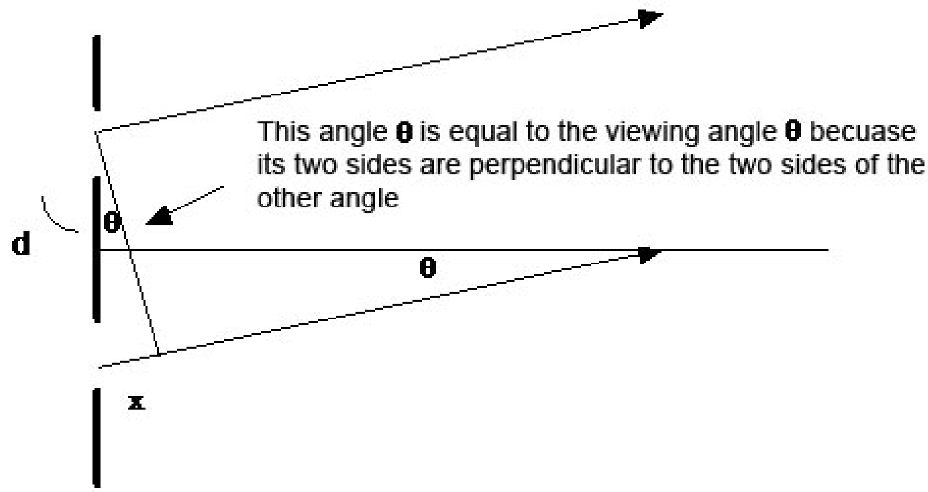


The incident laser light shining on the slits is *coherent*: at each slit, the light ray starts with the same phase. To reach the same point on the viewing screen, one ray needs to travel slightly farther than the other ray, and therefore becomes out of phase with the other ray. If one ray travels a distance equal to one-half wavelength farther than the other way, then the two rays will be 180° out of phase and cancel each other, resulting in destructive interference. No light reaches this point on the screen. At the center of the screen, the two rays travel exactly the same distance and therefore interfere constructively, producing a bright fringe. At a certain distance from the center of the screen, the rays will be one-half wavelength (or 180°) out of phase with each other and interfere destructively, producing a dark fringe. A bit farther along the screen, the rays will be one whole wavelength (or 360°) out of phase with each other and interfere constructively again. Farther still, the ways will be one and one-half wavelengths (or 360° + 180° = 540°) out of phase with each other and interfere destructively. Thus, the interference pattern contains a series of bright and dark fringes on the screen.

Let θ be the viewing angle from the perpendicular, as shown in the figure below:



Study the construction in Figure 3.



The small extra distance x that the lower ray needs to travel is $d \sin\theta$. If this distance is equal to an odd multiple of one-half wavelength, then the two rays will interfere destructively, and no light will reach this point on the screen:

$$\begin{aligned} &\text{interference minima at} \\ d\sin\theta &= N(\lambda/2) \\ &\text{for } N = 1, 3, 5, \ldots \end{aligned} \tag{1}$$

(An even value of N would separate the two rays by a whole number of wavelengths, causing them to interfere constructively.) Now, note that the expression $N = 2(n + 1/2)$ reproduces the odd numbers $N = 1, 3, 5, \ldots$ for $n = 0, 1, 2, \ldots$, so we can rewrite Eq. 1 as:

$$\begin{aligned} &\text{interference minima at} \\ d\sin\theta &= (n + 1/2)\lambda \\ &\text{for } n = 0, 1, 2, \ldots. \end{aligned} \tag{2}$$

Look at Figure 2 again. If y is the linear distance from the center of the pattern on the screen to the point of interference, and if the angle θ is small, then $\sin\theta \approx \tan\theta = y/L$. Thus, the positions of the minima are given by

$$y_n = (n + 1/2)\lambda L/d \quad \text{for } n = 0, 1, 2, \ldots, \tag{3}$$

and the distance between successive minima is

$$\Delta y = (y_{n+1} - y_n) = \lambda L/d. \tag{4}$$

The first part of this experiment involves measuring the positions of the interference minima and determining the wavelength of the laser light.

SINGLE-SLIT DIFFRACTION

When light passes through a single slit of non-zero width, rays from the different parts of the slit interfere with one another and produce another type of interference pattern. This type of interference — in which rays from many infinitesimally close points combine with one another — is called *diffraction*. We will measure the actual intensity curve of a diffraction pattern.

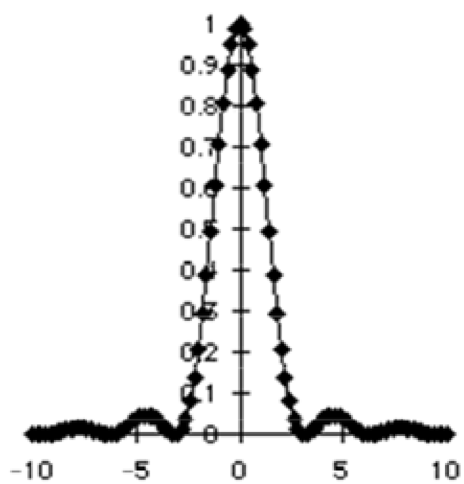
The textbook or the appendix to this experiment gives the derivation of the intensity curve of the diffraction pattern for a single slit:

$$I = I_0[(\sin\alpha)/\alpha]^2, \tag{5}$$

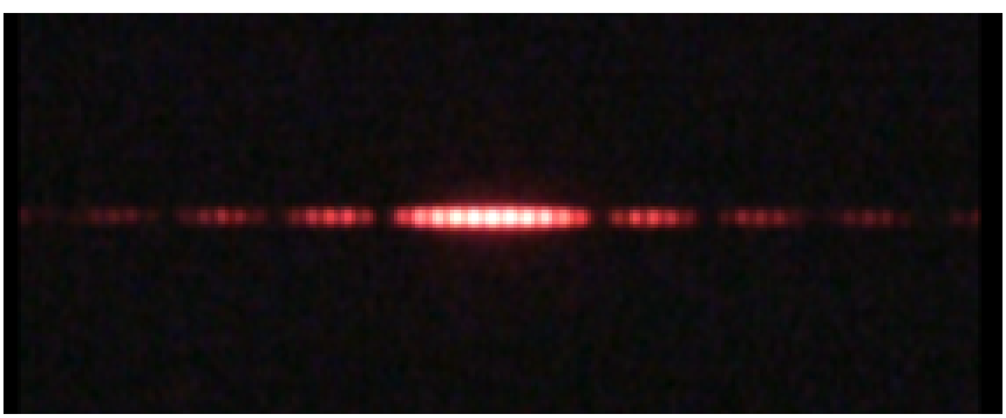
where

$$\alpha = \pi a \sin\theta/\lambda, \tag{6}$$

a is the slit width, and θ is the viewing angle. Here is a plot of the intensity I from Excel:



The image below demonstrates the intensity pattern; it shows the broad central maximum and much dimmer side fringes.



Let us locate the minima of the single-slit diffraction pattern. From Eq. 5, the minima occur where $\sin\alpha = 0$, except where α itself is zero. When α is zero, $\sin\alpha = 0$, and the expression $0/0$ is indeterminate. L'Hopital's rule resolves this ambiguity to show that $\sin\alpha/\alpha \to 1$ as $\alpha \to 0$. Thus, $\alpha = 0$ corresponds to the center of the pattern and is called the central maximum. Elsewhere, the denominator is never zero, and the minima are located at the positions $\sin\alpha = 0$ or $\alpha = n\pi$, with $n =$ any integer <u>except</u> 0. From Eq. 6, we find that:

$$\begin{gathered}\text{diffraction minima at}\\ a\sin\theta = n\lambda \\ \text{for } n = \text{any integer } \underline{\text{except}}\ 0.\end{gathered} \tag{7}$$

Note that the central maximum is twice as wide as the side fringes. The centers of the side fringes are located approximately (but not exactly) halfway between the minima where $\sin\alpha$ is either $+1$ or -1, or $\alpha = (n + 1/2)\pi$, with $n =$ any integer <u>except</u> 0:

$$\begin{gathered}\text{diffraction maxima approx. at}\\ a\sin\theta = (n + 1/2)\lambda \\ \text{for } n = \text{any integer } \underline{\text{except}}\ 0.\end{gathered} \tag{8}$$

(The maxima are only approximately at these positions because the denominator of Eq. 5 depends on α. To find the exact positions of the maxima, we need to take the derivative of I with respect to α and set it equal to zero, then solve for α.)

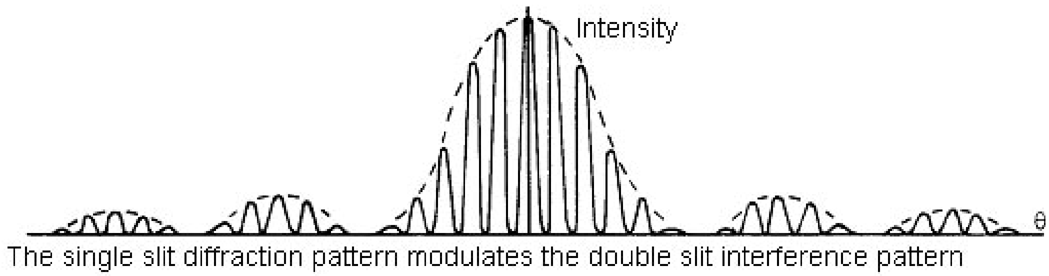
As mentioned above, the side fringes are much dimmer than the central maximum. We can estimate the brightness of the first side fringe by substituting its approximate position $\alpha = 3\pi/2$ into Eq. 5:

$$I(\text{first side fringe})/I_0 = 1/(3\pi/2)^2 = 0.045. \tag{9}$$

The first side fringe is only 4.5% as bright as the central maximum.

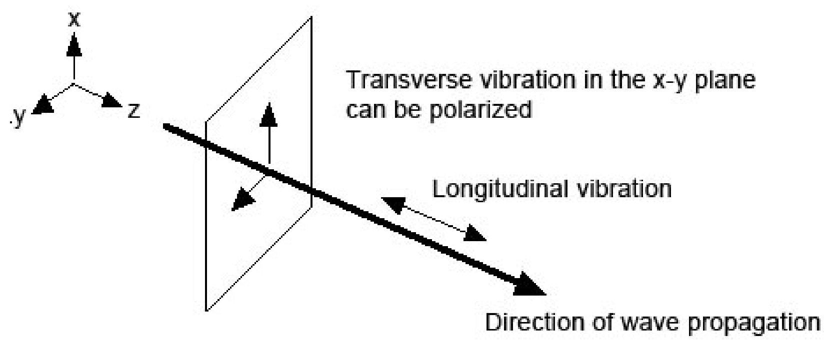
Note an important point about diffraction: As the single slit is made more narrow, the central maximum (and indeed the entire pattern) spreads out. We can see this most directly from the position of the first minimum in Eq. 7: $\sin\theta_1 = \lambda/a$. As we try to "squeeze down" the light, it spreads out instead.

Consider the double-slit interference setup again. Eq. 3 shows that the fringes are equally spaced for small viewing angles, but we now wish to determine the brightness of the fringes. If the two slits were very narrow — say, much less than a wavelength of light ($a \ll \lambda$) — then the central maxima of their diffraction patterns would spread out in the entire forward direction. The interference fringes would be illuminated equally. But we cannot make the slits too narrow, as insufficient light would pass through them for us to see the fringes clearly. The slits must be of non-zero width. Their central diffraction maxima will nearly overlap and illuminate the central area of the interference fringes prominently, while the side fringes of the diffraction pattern will illuminate the interference fringes farther from the center. A typical example is shown below.



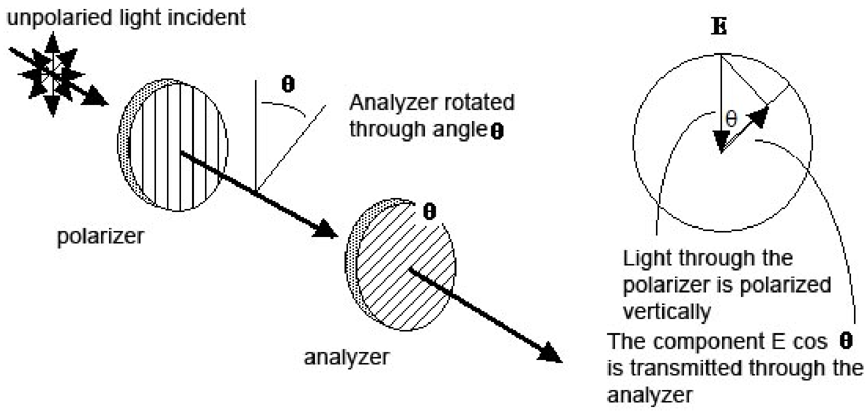
POLARIZATION

Consider a general wave moving in the z direction. Whatever is vibrating could be oscillating in the x, y, or z directions, or in some combination of the three directions. If the vibration is along the direction of wave motion (i.e., in the z direction), then the wave is said to be longitudinal. Sound is a *longitudinal* wave of alternate compressions and rarefactions of air. If the vibration is perpendicular to the direction of wave motion (i.e., in the xy plane), then the wave is said to be transverse. (Certain kinds of waves are neither purely longitudinal nor transverse.) Since one particular direction within the xy plane can be selected, a transverse wave can be *polarized.*



The simple fact that light can be polarized tells us that light is a transverse wave. According to Maxwell's equations, light is electromagnetic radiation. The electric and magnetic field vectors oscillate at right angles to each other and to the direction of wave propagation. We assign the direction in which the electric field oscillates as the polarization direction of light. The light from typical sources such as the Sun and light bulbs is *unpolarized*; it is emitted from many different atoms vibrating in random directions. A simple way to obtain polarized light is to filter unpolarized light through a sheet of Polaroid. Such a sheet contains long, asymmetrical molecules which have been cleverly arranged so that the axes of all molecules are parallel and lie in the plane of the sheet. The long Polaroid molecules in the sheet are all oriented in the same direction. Only the component of the incident electric field perpendicular to the axes of the molecules is transmitted; the component of the incident electric field parallel to the axes of the molecules is absorbed.

Consider an arrangement of two consecutive Polaroid sheets:



The first sheet is called the *polarizer*, and the second one is called the *analyzer*. If the axes of the polarizer and analyzer are crossed (i.e., at right angles to each other), then no light passes through the sheets. (Real polarizers are not 100% efficient, so we might not see exactly zero light.) If the axis of the analyzer were aligned parallel to that of the polarizer, then 100% of the light passing the polarizer would be transmitted through the analyzer. The diagram above shows that if the analyzer is oriented at an angle θ with respect to the polarizer, then a component of the incident electric field $E\cos\theta$ will be transmitted. Since the intensity of a wave is proportional to the square of its amplitude, the intensity of light transmitted through two polarizers at an angle θ with respect to each other is proportional to $\cos^2\theta$. This result is called *Malus' Law*, which we will test in this experiment.

An interesting situation arises if a third polarizer is inserted between two crossed polarizers. No light passes through the crossed polarizers initially, but when the third polarizer is added, light is able to pass through when the third polarizer has certain orientations. How can the third polarizer, which can only absorb light, cause some light to pass through the crossed sheets?

EQUIPMENT

At your lab station is an optics bench. A laser is located at one end of the bench, on a laser alignment bench, while a linear translator with a dial knob that moves the carriage crossways on the bench can be found at the other end. Between the laser and the linear translator are one or more movable component carriers. Fitted into a small hole in the linear translator is a fiber-optic probe connected to a high-sensitivity light sensor which, in turn, is connected by an extension cable to the ScienceWorkshop interface. Be careful with the probe. Do not bend the probe in a circle of less than 10-cm diameter at any given point. Also, do not bend the probe within 8 cm of either end. A slit of width 0.2 mm has been placed just in front of the probe to provide 0.2-mm resolution. (Note: Do not remove the Photometer Apertures slide from the translator and use it as a single slit.)

Light from the laser is transmitted through the probe to the high sensitivity light sensor, which provides an intensity reading. The linear translator (which is basically a carriage mounted on a threaded rod) moves the probe along the axis of the rod. An intensity plot of the pattern produced by a slit placed between the light source and the probe can be made by scanning the probe along the axis of the rod and taking readings from the high sensitivity light sensor.

The probe can be attached to the high sensitivity light sensor by slipping the optic output connector (BNC plug) of the probe over the input jack on the high sensitivity light sensor. A quarter-twist clockwise locks the probe to the high sensitivity light sensor; push the connector towards the sensor box and a quarter-twist counterclockwise disengages it.

The probe attenuates the light intensity reaching the selenium cell to approximately 6.5% of its value when the probe is not used. This makes measurements of absolute intensity impossible. However, for these experiments, only the relative intensities are needed.

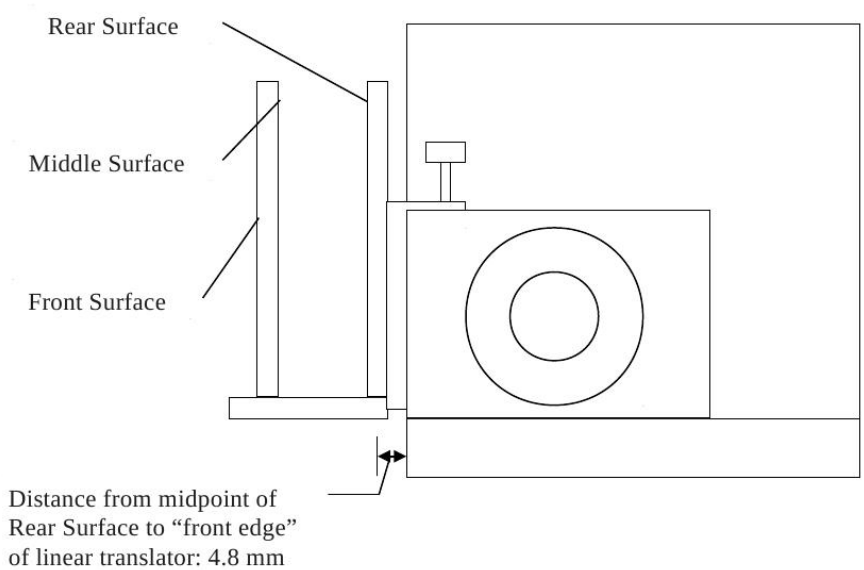
PROCEDURE PART 1: DOUBLE-SLIT INTERFERENCE

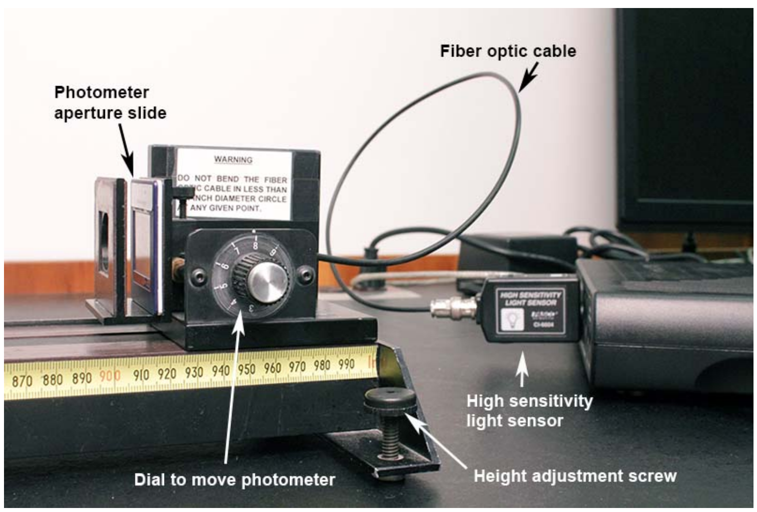
In this part of the experiment, we will locate only the minima of the interference pattern and measure the distance between them.

1. Open PASCO Capstone and choose the “Graph & Digits” option. Click the Hardware Setup tab to display the interface. Click on channel “A” and select “Light Sensor”. In the digits display box, click on “Select Measurement” and choose “Light Intensity”. Click “Record” to test out the sensor.

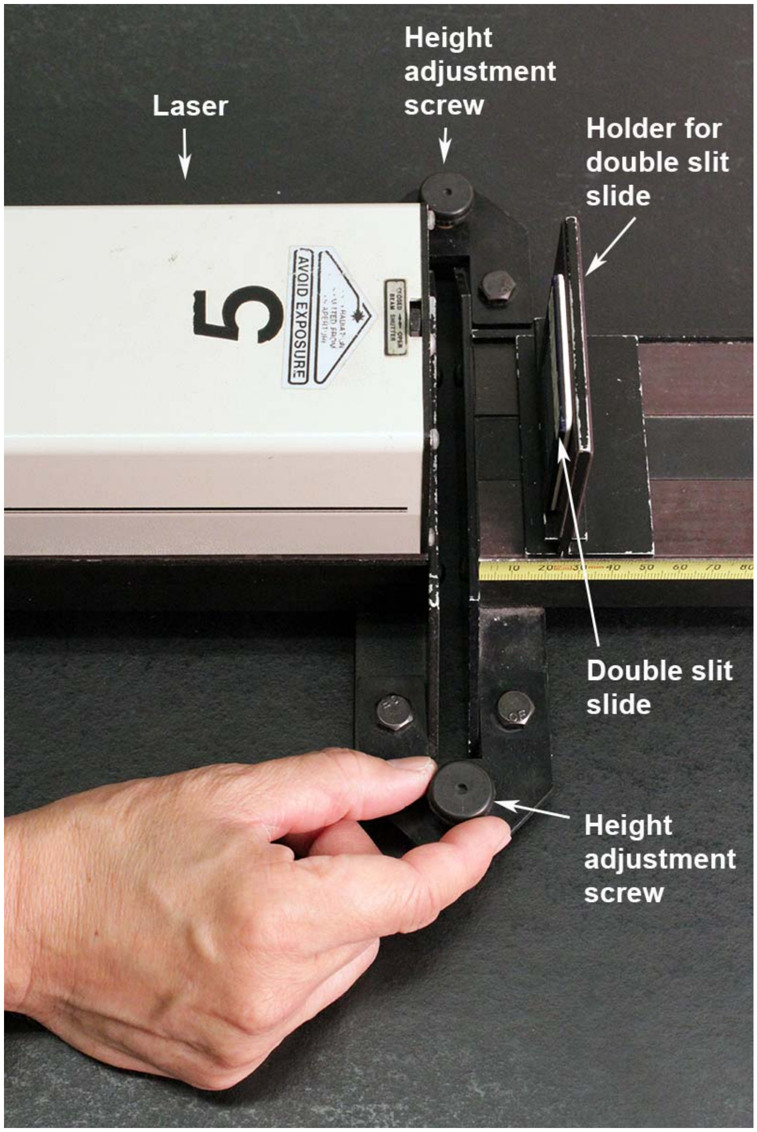
2. Look at the component carrier. A white line on the side of the carrier indicates the carrier position with reference to the meter scale on the optics bench. The white line is in the middle of the two vertical surfaces.

3. Study the translator carriage for a moment. At the back, a pointer line rides over a scale graduated in millimeters. One turn of the dial moves the pointer 1 millimeter, so the dial is reading in tenths of a millimeter. You can probably estimate hundredths of a millimeter on the dial scale. To begin aligning the system, move the translator carriage so the pointer is around the midpoint (approximately 24 mm) of the scale. Note there are three surfaces to which you can attach slides (see figure and image below). When using the Photometer Apertures slide, put it on the Rear Surface only, closest to the fiber optic cable. Also note there isn’t a white line to indicate the linear translator position with reference to the meter scale on the optics bench. Using the “front edge” of the translator as the indicator, the middle of the Rear Surface is offset by 4.8 mm.



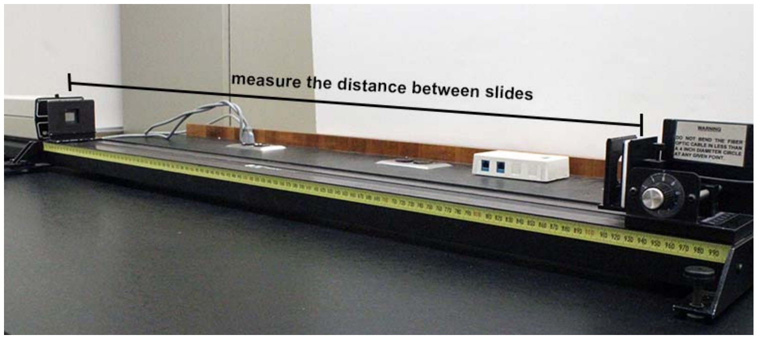


4. Start aligning the laser. Remove all slides (which attach magnetically to the carriers and the rear surface of the translator carriage) from the optics-bench setup. Turn on the laser and align the beam so it hits the center of the fiber-optic cable end. You can do this by adjusting the laser alignment bench screw at the back of the laser to set the beam at the right level so that when the translator carriage is moved by turning its dial, the end of the fiberoptic cable moves across the center of the laser beam.

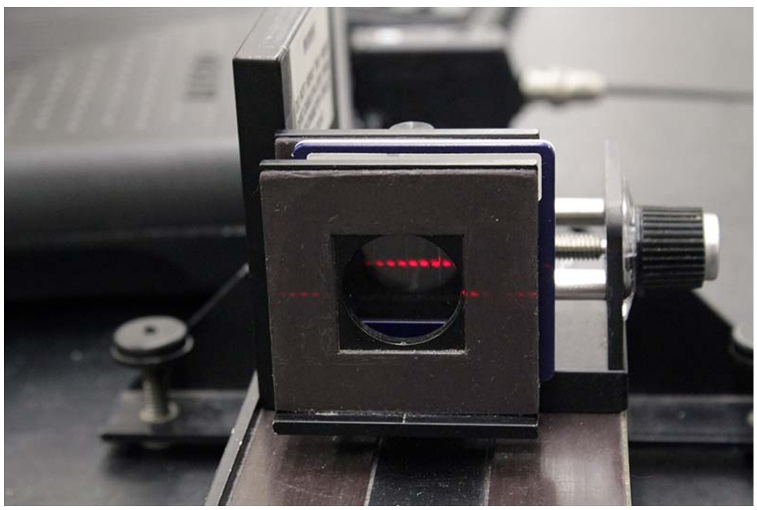


Be careful not to bump the laser, laser alignment bench, or optics bench when you are working later on the experiment so as to disturb the alignment. This is an easy mistake to make, especially with more than one person working on the experiment!

5. Place the Photometer Apertures slide on the rear surface of the translator stage. This slide has four single slits, but do not confuse it with the slides with single and double slits whose patterns you will be measuring. Position the 0.2-mm slit in front of the fiber optic terminal so that the laser beam is centered on it, shining into the fiber-optic cable end. The smaller the aperture you use the more detail you can detect in the pattern; however, you are also allowing less light into the light sensor and may not be able to detect the dimmest parts of the pattern. We suggest you use the 0.2-mm aperture for the double- and single-slit measurements below, but feel free to try other apertures if you think they would improve the results.



6. Position the narrowest double slit on the component carrier close to the laser so that when the laser is turned on, the double-slit fringe pattern is thrown onto the aperture slide. Note the modulated form of the pattern. Either start recording data or use "Monitor Data". Change the "Gain" on the light sensor to get a value between 1 and 5 volts.



7. Carefully record in the "Data" section the positions of the slit slide and the aperture slide using the optical-bench scale. The difference between these two positions is the distance L in Figure 2 and Eq. 3.

8. As you turn the dial of the translator stage, the aperture will move across the pattern. Measure and record the distances between the minima for five successive fringes carefully. Average the five distances. The translator stage may have "backlash": when reversing its direction, you need to turn the dial a perceptible distance before the stage begins to move. Therefore, turn the dial in only one direction when making the actual measurements.

9. Using Eq. 4, calculate the wavelength of the laser light. Compare it with the actual wavelength of 632.8 nm, and calculate the percentage error. (This is an atomic transition in neon atoms.)

PROCEDURE PART 2: POLARIZATION

1. The laser is not useful for polarization experiments because the laser beam is already partially polarized and the plane of polarization is rotating with time. You can check this by placing a polarizer between the laser and the fiber optic probe, and observing the Capstone reading. Instead, set the "Gain" on the light sensor to "1". Remove all slides, including the apertures slide. Put the Incandescent Light Source on the optics bench so the end with the light coming out is about 50 cm from the linear translator. Turn on the light source and adjust the bulb to get a bright beam to fall on the fiber-optic probe end. Place a polarizer on one of the component carriers and one on the front surface of the translator carriage.

2. Note that the polarizers are graduated in degrees and you can read off the angle from the marker on the bottom of the component carrier. Set both angles to zero for full transmission. Click "Record" to monitor the light sensor output. Adjust the gain of the light sensor if necessary.

3. Take intensity readings for every $10°$ of rotation of one of the polarizers from $0°$ to $90°$.

4. Enter the angle and intensity data in two columns in Excel. In a third column, calculate $I_0 \cos\theta$. In a fourth column, calculate the theoretical intensity $I_0 \cos^2\theta$. Chart with Excel, and compare the experimental and theoretical curves. Is the cosine-squared curve clearly a better fit than the cosine curve? You may print out this Excel page for your records.

5. As a final polarization measurement, experiment with three polarizers. Record the data requested below in the "Data" section.

   a. Record the intensity of the light with no polarizers. You may have to change the gain on the sensor.

   b. Add one polarizer between the source and sensor, and record the intensity.

   c. Add a second polarizer, adjust for minimum intensity (crossed polarizers) and record the intensity.

   d. Now insert a third polarizer between the first two, and rotate it. For what angle of the middle polarizer (with respect to the first) does a maximum of light pass through all three polarizers?

   e. Record the intensity of light that passes through at the maximum position.

   f. Convert the measurement in step e to a decimal fraction of the total intensity (found in step a).

   g. What should the theoretical fraction be?

ADDITIONAL CREDIT PART 1: SINGLE SLIT (2 mills)

Measure the intensities of the side fringes, and compare them with the theoretical values.

1. Following the reasoning leading up to Eq. 8, calculate the intensity of the second side fringe as a decimal fraction of the intensity of the central maximum.

2. Set the "Gain" on the light sensor to "1", and remove the incandescent light source. Recheck the laser alignment as in step (4) of the double-slit procedure. Position the apertures slide on the 0.2-mm slit.

3. Insert a single slit on one of the component carriers. Check that you are obtaining a nice single-slit pattern as in Figure 4 or 5 across the apertures slide.

4. In the "Data" section table, record the intensity of the central maximum, as well as the intensity of the first and second side fringes, in one column. You can locate the maxima by rotating the translator-stage dial while observing the light sensor output. In the second column, convert the intensities to a decimal fraction of the intensity of the central maximum. Record the theoretical value next to the results of the fractional intensities of the side fringes.

ADDITIONAL CREDIT PART 2 (3 mills)

Measure a single-slit intensity curve, and compare it with the theoretical curve.

1. Call up Excel on your computer. Enter the column of distance measurements for every 0.2 mm by using a "Series" operation.

2. Set up the narrowest slit on the optical bench. Start at the center of the central maximum, and record intensity readings every 0.2 mm past the second minimum (so that you cover the first side fringe) in the next column of Excel.

3. You need the slit width to calculate the theoretical curve from Eqs. 4 and 5. Measure this width with the traveling microscope.

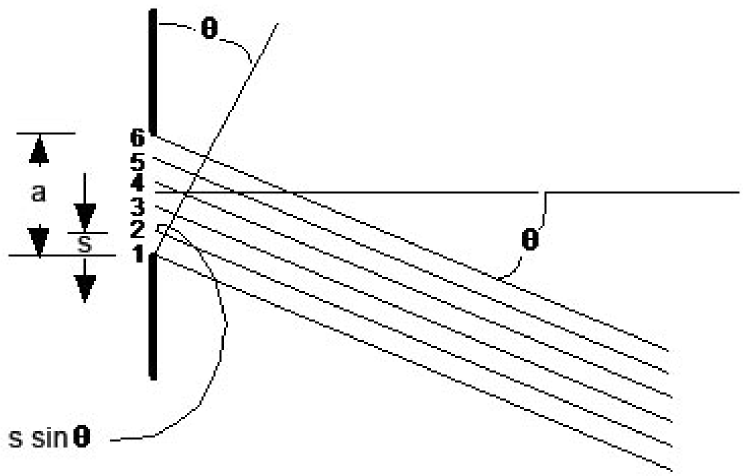
4. In the third column, compute the theoretical intensity from Eq. 4. Enter the formula correctly into the first cell; then use the "Fill Down" operation.

5. Graph your theoretical and experimental curves (normalized to the intensity at the center of the central maximum). If all looks well, you may print your chart out with the data to keep for your records.

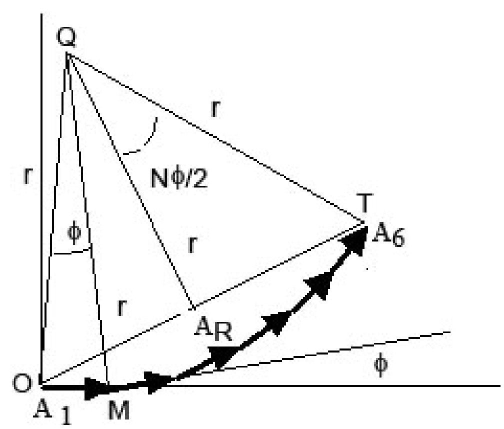
APPENDIX: SINGLE-SLIT THEORY CONTINUED

We will use a geometrical, or *phasor*, method to derive Eq. 5 for the intensity curve of the single-slit diffraction pattern.

Suppose that instead of a single beam of light passing through a slit of width a, there are N tiny sources of light (all monochromatic and coherent with each other) which are separated from each other by a distance s in such a way that $Ns = a$. We will start with six light sources so that our pictures are clear, but will eventually let N go to infinity.



In Figure 10, we are looking at the light rays coming from the sources that make an angle θ with the horizontal. Observing the figure closely, we see that the ray from source 2 travels a distance $s \sin\theta$ greater than the ray from source 1 en route to the viewing screen on the right (not shown in the figure). Thus, the light from a given source is out of phase with the light from the source just below it by a phase $(2\pi s \sin\theta)/\lambda$, which we denote ϕ for brevity. We will assign an amplitude A to each source and, with the phase difference ϕ, draw a diagram showing the addition of the light rays at some angle θ (Figure 11).



We see that each vector makes an angle ϕ (phase difference) with the preceding one, and the resultant vector is the total *amplitude* of light seen at angle θ. When we determine what OT $= A_{\mathrm{R}}$ is in terms of ϕ and A, we square the result to obtain the total *intensity* of light at angle θ.

Note that the vectors A_1 through A_6, each of equal magnitude A, lie on a circle whose radius is OQ $= r$. Since the angle OQM is ϕ, it follows that $A = \mid A_1 \mid = 2r\sin(\phi/2)$ (some steps have been skipped here). But angle OQT is $N\phi$ (where $N = 6$ in this case), so $A_{\mathrm{R}} = 2r\sin(N\phi/2)$. Solving for A_{R} in terms of A and ϕ, we find

$$A_{\mathrm{R}} = A\sin(N\phi/2)\,/sin(\phi/2). \tag{10}$$

This is the amplitude of light from N slits, where $N = 6$ for the case we are illustrating. We now wish to let N go to infinity. As N approaches infinity, s approaches 0, but Ns approaches a (the slit width). Thus, $N\phi$ approaches Φ, the total phase difference across the entire slit:

$$\Phi = (2\pi a/\lambda)\,\sin\theta. \tag{11}$$

Thus, Eq. 10 becomes

$$A_\mathrm{R} = A\sin(\Phi/2)/\sin(\Phi/2N). \tag{12}$$

The angle $\phi = \Phi/N$ becomes infinitesimally small, so we can replace the sine term in the denominator of Eq. 12 with the angle itself:

$$A_\mathrm{R} = A\sin(\Phi/2)/(\Phi/2N). \tag{13}$$

Finally, $NA = A_\mathrm{T}$ (the total amplitude of light from the slit), so

$$A_\mathrm{R} = A_\mathrm{T}\sin(\Phi/2)/(\Phi/2). \tag{14}$$

If we let $\alpha = \Phi/2 = (\pi a/\lambda)\sin\theta$, then

$$A_\mathrm{R} = A_\mathrm{T}(\sin\alpha/\alpha). \tag{15}$$

The intensity is proportional to the square of the amplitude, so

$$I = I_0[(\sin\alpha)/\alpha]^2. \tag{16}$$

This is Eq. 5.

DATA

Procedure Part 1:

5. Slit-slide position = ______________________________

   Aperture-slide position = ______________________________

   L = ______________________________

6. Positions of 5 minima = ______________________________

   ____

   ____

   ____

   ____

   Average difference = ______________________________

7. Measured distance between inside edges = ______________________________

   Measured slit width = ______________________________

   d from measurements above = ______________________________

   Nominal d on slide = ______________________________

8. Calculated wavelength = ______________________________

   Percentage error = ______________________________

   Show your calculation of the wavelength neatly below.

Procedure Part 2:

3. You may pring out your data in Excel.
4. You may pring out your data in Excel.
5. a. Intensity with no polarizers = ______________________________

   b. Intensity with one polarizer = ______________________________

   c. Intensity with crossed polarizers = ______________________________

   d. Angle of middle polarizer = ______________________________

   e. Intensity with third polarizer = ______________________________

   f. Fraction = ______________________________

   g. Theoretical fraction = ______________________________

Additional Credit Part 1 Data:

	A	B	C	D
1	fringe	measured intensity	fractional intensity	theoretical intensity
2	central			
3	1st side			
4	2nd side			