PHOTON

and

PHOTON2

LABS FOR THE PHOTON/PHOTON2 EXPERIMENT KIT

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LABS FOR THE PHOTON/PHOTON2 EXPERIMENT KIT
Contents

PHOTON2 Kit Scavenger Hunt

Objectives:

- To become familiar with contents of the PHOTON2 optics kit
- To build common optical assemblies from kit components

Equipment/Supplies:

- The PHOTON2 laboratory kit

Procedure:

1. Identify each of the following items in the PHOTON2 Kit. Consult the detailed kit photos if necessary. What is each item used for?
    a. Optical power meter
    b. Linear translation stage
    c. Optical breadboard
    d. Mounted first surface mirrors (<u>Do not touch the mirror surface!)</u>
    e. Plate holder
2. Construct each of the following subassemblies, using the parts listed. Consult the detailed kit photos if necessary.
    a. LENS HOLDER ASSEMBLY: Use one 3" post holder, one 3" post, one bar-type lens holder, one convex lens, one base plate. Create a lens holder assembly that can be used to mount lenses on the optical breadboard. The base plate is optional (the post holder may be attached directly to the breadboard), but it allows the assembly to be positioned between holes on the breadboard.
    b. MICROSCOPE OBJECTIVE ASSEMBLY: Use one 3" post holder, one 3" post, the microscope objective holder, microscope objective and base plate. Create a microscope objective holder assembly on a sliding base plate.
    c. BEAM SPLITTER MOUNT ASSEMBLY: Use one 2" post holder, one 2" post, rotational stage with base plates, and cube beam splitter. Assemble the stage to the post and post holder and position the beam splitter for rotation about a vertical axis.
    d. POLARIZING FILTER ASSEMBLY: Use one 2" post holder, one 2" post, rotational stage without base plate, polarizer. Assemble the stage to the post and post holder for rotation about a horizontal axis. You may need to remove the small screws holding the top and bottom plates to the rotational stage. (Be careful not to lose the screws!) Insert the polarizer and rotate. Notice that you can rotate the polarizer itself, or rotate it within the rotational stage assembly. Only the rotational stage has degree markings, however.

   e. TILT TABLE ASSEMBLY: Use one 2” post holder, one 2” post, and the tilt table. Assemble to create a mounting platform to be used with the laser or ray box. Leave this assembly in place, to hold the laser in the next step of the procedure.

3. Identify and test the three light sources. The laser and the ray box can each be mounted on the tilt table assembly. (The ray box has its own mounting hardware as well.) NOTE THE CAUTIONS ASSOCIATED WITH EACH!

   a. Low power polarized HeNe laser (Class 3A). Note that the beam angle with the horizontal may be adjusted by turning the tilt table's brass adjustment screw.

   The laser produces extremely intense collimated light. Do not look directly into laser cavity, or at any reflections caused by shiny surfaces. Keep the beam at bench level so as not to shine the beam accidentally into the eyes of another person.

   b. Gas spectrum tube (Hydrogen or Helium) and power supply

   The power supply uses a high voltage, and the tubes become quite hot. Be careful inserting tubes into the metal terminal brackets. Let the tube cool before removing. Do not leave the tube on longer than necessary, since this may shorten its useful life.

   c. PASCO Ray box: Choose one or several rays (ray side of the box) or the 2-dimensional object for lens experiments. Note that the slide for the ray side is somewhat delicate. Use care when adjusting slide to obtain rays.

   The ray box becomes warm after being on for a few minutes. There is no on-off switch; the unit is energized when plugged in.

Applications/Explorations:

   d. Suppose you needed to be sure the laser beam was aligned with a row of holes on the breadboard, and did not rise or fall as it traveled from one end of the board to the other. How could you align the beam? How could you check your alignment to be sure it is correct?

   e. How could you align two mounted lenses with the ray box, ensuring that the centers of the lenses are aligned with the center of the arrow pattern on the ray box?

Spectra of Light Sources

Safety Notes

Do not look into the laser cavity or at any reflections of the laser from shiny surfaces. Keep the beam at bench level so as not to accidentally shine the beam in the eyes of another person.

The spectrum tubes use a high voltage power source. Do not touch the power supply terminals. The tubes become very hot; allow them to cool before touching.

Objectives:

- To examine the wavelength characteristics of several light sources
- To calibrate a grating spectrometer using the light from a gas spectrum tube

Equipment/Supplies:

- Hydrogen spectrum tube and power supply
- Other light sources as available (incandescent, fluorescent, "energy saver" fluorescent, sodium vapor, laser, colored filters, etc.)
- Quantitative spectrometer
- Card mounted diffraction gratings

Theoretical Overview:

We can learn a lot about a light source by studying its spectrum. For example, the spectrum of the sun is composed of a complete "rainbow" crossed by dark lines due to absorption of certain wavelengths by the sun's atmosphere. An excited gas at low pressure produces an emission spectrum, bright lines against a dark background. As pressure or temperature increases, the lines expand into wider bands. Solid objects produce a continuous spectrum with a wavelength distribution that depends on the temperature of the object.

In this lab you will use a diffraction grating to separate visible light into its component wavelengths. The grating spectrometer can provide a *quantitative* reading of the wavelengths present and the card mounted grating gives a *qualitative* look at the wavelengths available. The card mounted grating can be used directly (looking into the grating toward the source) or indirectly (shining the light through the grating and projecting the spectrum on a screen). The indirect method must be used for laser sources, where direct viewing may damage the eye.

Procedure:

<u>Part 1: A qualitative look at wavelengths of some sources</u>

Hints on using the diffraction grating to observe spectra: A normal room is full of light from many sources. To isolate one source of light, you need to eliminate as much of the ambient (background) light as possible. Turn off all room lights and close the curtains or blinds, if possible. Get as close as safely possible to the source you are observing, and hold the grating near your eye. Use your hand to block out room light. A paper tube held between the grating and source will also help to block out ambient light

1. Look through the grating at each of the light sources EXCEPT the laser. To see the spectrum, look through the grating *to either side of the light source*. Note that more than one complete spectrum pattern may be visible. Focus on one of these patterns and record how many colors are visible. Describe the spectrum using words like "line" (a sharp line of color), "band" (a broader line of color) and "continuous" (like a rainbow).
2. To see the laser spectrum, shine the laser onto a piece of white paper placed on a table. Look through the grating at the spot of laser light on the paper. DO NOT LOOK DIRECTLY INTO THE LASER! Record the color(s) you see.
3. To view the colors transmitted by a filter, place the filter in front of the incandescent source and view it through the grating. The effect of the filter is easier to see if you begin by viewing the spectrum of the light without the filter and then move the filter into place.

Part 2: Calibrating a spectrometer (quantitative measurements)

When you step on a bathroom scale, how do you know your weight is correct? You are assuming that the scale is *calibrated*; that is, the numbers give an accurate measurement of weight. You can calibrate a scale by placing known weights on it and adjusting the dial to read correctly. In this experiment, you will calibrate a spectrometer by using a light source that gives off light at known wavelengths.

1. Place the hydrogen spectrum tube near the entrance slit of the spectrometer and observe the lines of the hydrogen spectrum. (Do not touch the tube when it is operating!) The actual wavelengths of these lines are

Red, 656 nm

Green-Blue, 486nm

Violet, 434 nm

Violet, 410 nm

Record the observed wavelengths for each color (the number on the spectrometer), which will probably be different from the actual wavelengths. Note: The room must be very dark to see the 410 nm line, and your eyes must be thoroughly dark-adapted.

2. To make a calibration curve, plot a graph of actual wavelength (y axis) versus observed wavelength (x axis). Draw a smooth curve through the points. You can now use this curve to "correct" the readings of the spectrometer.
3. Replace the hydrogen spectrum tube with a second gas tube, a sodium vapor lamp, or an energy saving fluorescent bulb. Record the colors and wavelengths you see in the spectrometer. Use your calibration curve to determine the actual wavelengths of this "unknown" source.

Analysis (calculations/observations) :

Qualitative observations:

1. Which light source has the fewest colors in its spectrum?
2. Which light source has the most colors in its spectrum?

3. Do the spectra of the filters contain only the color of the filter, or are other colors present?
4. Describe the spectrum of the gas tube source and the spectrum of the incandescent source. How are conditions different for electrons in a low-pressure gas compared to a solid tungsten filament? How does this explain the difference in the spectra of the two sources?

<u>Calibration curve (quantitative measurements);</u>

1. Use the calibration curve to determine the actual wavelengths for the “unknown” source. Record the actual wavelengths for the "unknown" source in the data table.
2. If the actual wavelengths for the "unknown" source are available, comment on the accuracy of your calibration curve. What were the sources of error in making this calibration curve? How could you minimize these sources of error?

Applications/Explorations:

1. How could a crime lab technician use a spectrometer to determine the composition of a substance found at a crime scene? What if the substance is a solid- how could the spectrum be obtained?
2. Helium was discovered on the sun before it was seen on Earth. How can that be?
3. Spectral lines of elements are the same in space as they are on Earth. If a star if moving, the light it emits may be Doppler shifted when seen from Earth. This causes a star's light to appear redder or bluer, depending on the direction of motion. What is the relative earth/star motion when the star looks redder? Bluer? (Hint: Do an Internet web search for the Doppler shift in Astronomy.) What if a star's spectrum is alternates between redder and bluer?
4. When you look at the spectrum of a color filter, what effect does the spectrum of the white light source have on the results? How could you minimize the effects of the white light source, so that you obtain the spectrum transmitted by the filter?
5. How can you safely observe the spectrum of the sun? What are the dark lines
6. Some of the lines in the gas tube spectra are brighter than others. Look again at the hydrogen and helium gas tubes. Which lines are bright and which are dim? Why are some lines brighter? Look at the NIST (National Institute of Standards and Technology) web site for information on the descriptions of spectral lines of elements and the energy levels involved. http://physics.nist.gov/PhysRefData/Handbook/index.html

Spectra of Light Sources
Data/Results

Part I: Qualitative Observations

Type of Source	Description of spectrum/colors seen

Part II: Calibration

Calibration Data for graph

Color	Actual wavelength	Observed wavelength
Red	656 nm	
Green-blue	486 nm	
Violet	434 nm	
Violet	410 nm	

"Unknown" source spectrum

Type of source_______________________________

Color	Observed wavelength	Actual wavelength from graph)

The Pinhole Camera

Objectives:

- To demonstrate the rectilinear propagation of light by constructing a pinhole camera viewer.
- To produce a pinhole photograph

Equipment:

- Small carton or shoebox (an oatmeal container also works well)
- Micrometer
- Sewing needle
- Pencil with eraser
- Emery paper
- Opaque tape (such as electrical tape)
- 2 inch diameter piece of thin aluminum, such as a flattened piece from a soft drink can
- Black and white paper film, developer and fixer*
- Darkroom supplies: rubber gloves, 2 small trays, large pail of rinse water

*For developing small quantities of film, liquid concentrates are easier to work with than powders. For example, Ilford ® Multipurpose Developer and Ilford Fixer may be mixed in small quantities as needed, and they are available at many full service photography shops. Before beginning, check local chemical disposal regulations for silver bearing waste.

Theoretical overview:

A pinhole camera is the simplest of imaging devices- it consists of a light-tight box with a tiny pinhole centered on one end. The film is placed on the inside of the box on the end opposite the pinhole. (Figure 1) The shutter may be any opaque piece of cardboard or tape. When the shutter is opened, exposing the pinhole, an image forms on the film because rays of light from the top of the object do not overlap rays from the bottom of the object. Because the pinhole is small, exposure times are very long compared to those with a lens camera.

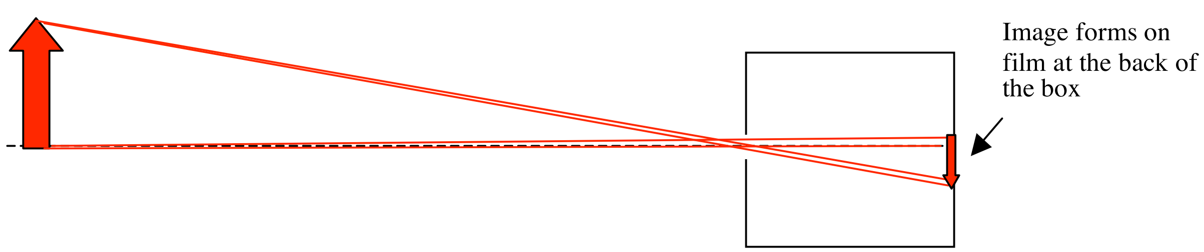


Figure 1 - The pinhole camera

The photographs taken by a pinhole camera are somewhat startling because of the large depth of field. That is, objects both near to the camera and far from it are equally in focus. Many art photographers are enthusiastic pinhole camera users, and several websites are devoted to pinhole photography. (See for example, www.pinhole.org)

Procedure:

1. Cut a hole approximately 5 cm square in the center of one end of the box. Decide how you will hold the film in place on the opposite wall of the box. You can simply use tape, or you may construct a "film holder" out of cardboard strips.
2. The size of the pinhole depends on the depth of the box (the "focal length" of the pinhole camera). The hole diameter is calculated from the equation $D = 0.047\sqrt{f}$ where f is the distance from the pinhole to the film.
3. To create a "drill" to make the pinhole, open the jaws of the micrometer to the width calculated in step 2. ("D") Insert the needle between the jaws. Mark the needle to indicate the location on the needle that has the same width as the micrometer opening. (Figure 2) When inserting the needle to create the pinhole, do not push it past this mark.

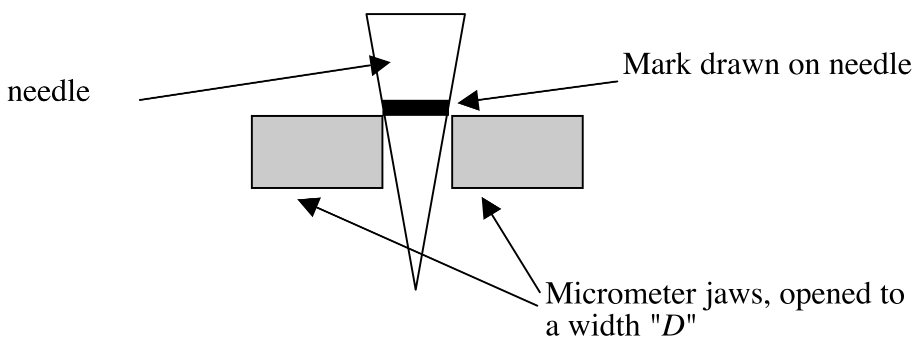


Figure 2 - preparing the needle "drill"

4. Insert the "eye" end of the needle into the eraser end of the pencil. This will allow you to more easily handle the needle as you drill the pinhole.
5. Flatten the piece of aluminum as much as possible. Slowly insert the needle into the metal, turning it as you push. When the needle barely pierces the aluminum, turn the piece over and drill from the other side. Do this several times, until the mark on the needle is reached.
6. Using fine emery paper, gently smooth the hole on both sides. An ideal pinhole is perfectly round and flat with razor thin edges.
7. Mount the pinhole over the opening in the side of the box and seal the edges with tape. (Black electrician's tape works well.) Be sure the edges and corners of the box are light tight by sealing any cracks with tape. Remember to leave an opening for the film!

8. This step needs to be done in a darkroom. (A red safelight may be used.) In the darkroom, load the film into the box, sensitive (emulsion) side toward the pinhole. Be sure the box is well sealed before leaving the darkroom and that the pinhole is covered with a tape or cardboard "shutter".
9. To make an exposure, place the box on a sturdy flat surface, preferable outdoors. Remove the shutter to expose the film. On a sunny day, begin with a 5-6 second exposure. Be sure to replace the shutter before returning to the darkroom.
10. Develop, rinse, fix and rinse the film again, according to the manufacturer's directions. If the film darkens immediately, try a shorter exposure. If the image is too light, use a longer exposure.

Conclusions/Observations:

Describe the image you created- was it sharp or blurred? Compare your photograph to one taken by a regular (lens) camera.

Applications/Explorations:

1. Photographs taken by pinhole cameras of large, non-luminous objects (like buildings or monuments) require very long exposure times. Two features of photographs taken with pinhole cameras are that objects in motion (people walking by, cars, etc) don't appear in the finished photograph and the photographs have a slightly blurry quality. Explain how both of these effects happen.
2. The blotchy shadows under a leafy tree are actually pinhole images of the sun. How does this occur? What will the shadows look like during a solar eclipse? (If you get a chance to witness a summertime solar eclipse, be sure to look at the shadows under a large, leafy tree- it's an amazing sight!)
3. What happens if you make the pinhole too large? Draw a ray diagram to show what happens to the image. What happens if the pinhole is too small? (At some point, wave optics is needed to describe the situation.)
4. The *f-stop* of a pinhole camera is the focal length (length of the box from pinhole to film) divided by the pinhole diameter. What is the f-stop for your camera? Compare to typical values for a lens camera. Because of the large f-stop, requiring long exposure times, exposures with pinhole cameras are often subject to *reciprocity failure.* What is this, and why does it limit most pinhole photography with film paper to sunny days?
5. One photographer who favors pinhole cameras says he never needs a telephoto lens to obtain a larger image- he just makes a longer camera. Explain why this is so, using the equation for similar triangles. For a fascinating look at pinhole photography, see Smithsonian, May 2000, *The Pinhole Point* (pg 124 ff)

Multiple Images in a Plane Mirror

Objectives:

- To observe multiple images formed by two plane mirrors
- To develop the graph of an equation that is a step function

Equipment /Supplies:

- Two plane mirrors, held vertical. You can use clothespins or other items from the lab. If you use front surface mirrors, <u>be careful to handle only by the edges</u>.
- Protractor
- Common pin or other small object
- Cardboard or other base to support the object and mirrors

Theoretical overview:

The law of reflection states that the angle of reflection is equal to the angle of incidence. When the reflected ray from one mirror is incident on a second mirror, multiple images are formed. This effect is familiar from dressing room mirrors that provide multiple views of a customer trying on clothes.

In this lab, you will observe multiple images formed by two plane mirrors as the angle between the mirrors changes. Unlike most of the phenomena you study in classical physics, the number of images is not a smooth, continuous function of angle, but is a "step function" that changes abruptly from one value to the next.

Procedure:

1. Stand the mirrors so that their reflective surfaces are vertical. The mirror surfaces should be protected if they are front surface mirrors. (You don't want to use your most expensive front surface mirrors for this experiment!) If you tape the mirrors to cardboard, be sure to tape the non-coated side only.
2. Align the vertical mirrors so that the angle between them is 180º, that is, so they are end-to-end in a straight line. Place the pin or other small object a few centimeters in front of the mirrors as shown in Figure 1.
3. Look into the mirrors from a point beyond the object. If the edges of the mirrors are in contact, you may see an image where mirrors touch. Ignore this image. (You won't see it if there is a gap between the mirrors)
4. Slowly rotate the ends of the mirrors together, reducing the angle between them. (Figure 1) Note that additional images appear in the mirrors as the angle changes. The image at the center, between the two mirrors, is only visible if the mirrors stay in contact.
5. Return the mirrors to the original position (180º). Now decrease the angle again, measuring the angle between the mirrors *each time a new set of images appears*. Continue to reduce the angle between the mirrors for as long as you can see and count the images. Record the angles and the number of images on the data sheet.

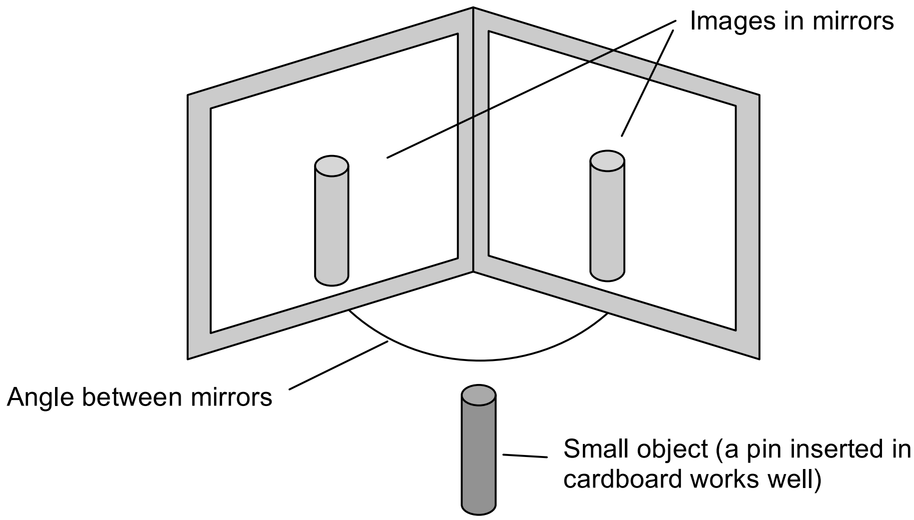


Figure 1

Analysis (calculations/observations) :

Make a graph of number of images versus angle between the mirrors from 180º to the smallest angle you could observe. Do not try to fit a smooth curve to the data, but draw "steps" to indicate how many images are observed at each angle.

Conclusions:

Why does the graph show steps instead of a smooth function? What do you notice about the number of images as the angle between the mirrors becomes smaller? Can you think of other physical quantities that are step-like rather than continuous?

Applications/Explorations:

1. Can you find a mathematical expression that describes the function you plotted in this experiment? Test your formula by applying some of the angles from your table, to see if it gives the correct number of images. Then use your formula to predict the number of images for smaller angles than those used in the experiment. How many images would there be if the mirrors were parallel (0º angle between them)?
2. Use the law of reflection and geometry to show that the image formed in a plane mirror is the same size as the object, and that the image distance is the same as the object distance.

Multiple Images in a Plane Mirror
Data/Results

Number of images	Angle between mirrors
	180°

Snell's Law

Safety Notes

Do not look into the laser cavity or at any reflections of the laser from shiny surfaces. Keep the beam at bench level so as not to accidentally shine the beam in the eyes of another person. The ray box becomes very warm, with use; use caution.

Objectives:

- To demonstrate "Snell's Law"
- To experimentally determine the index of refraction of a piece of plastic

Equipment /Supplies:

- HeNe laser, laser pointer or ray box (set for one ray)
- Rectangular prism from the acrylic shapes kit
- Ruler and protractor
- Graph paper

Theoretical overview:

When light is incident on a surface, some of the light is reflected and some of the light is refracted. The reflected light travels away from the surface at an angle equal to the angle of incidence. The refracted light is transmitted through the material at an angle that is generally different from the incident angle. (Figure 1)

The refracted angle, θ_2, depends angle of incidence, θ_1, the index of refraction, n_2, of the material, and the index of refraction of the incident material, n_1. Notice that the angles are measured from the normal (perpendicular) line to the surface.

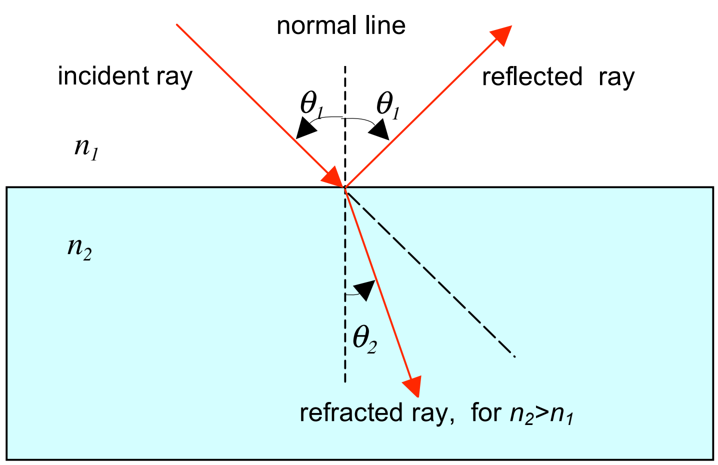


Figure 1 - Reflection and refraction at a surface for the case where light travels more slowly in the second medium.

The relationship between the angles and the two indices of refraction is give by Snell's law:

$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

Snell's law may be derived from the geometry of a plane wave as it bends at the surface between the two media. It may also be derived from a calculation of the quickest path from a point in the first medium to a point in the second (Fermat's principle of least time.) Snell discovered the law that bears his name by experiment.

Procedure:

1. Carefully trace the outline of the plastic prism on a piece of paper
2. Remove the shape, and draw a normal (perpendicular) line, as shown in Figure 2. Carefully draw lines making angles of 20º 30º· 40º· 50º· and 60º· with the normal line.

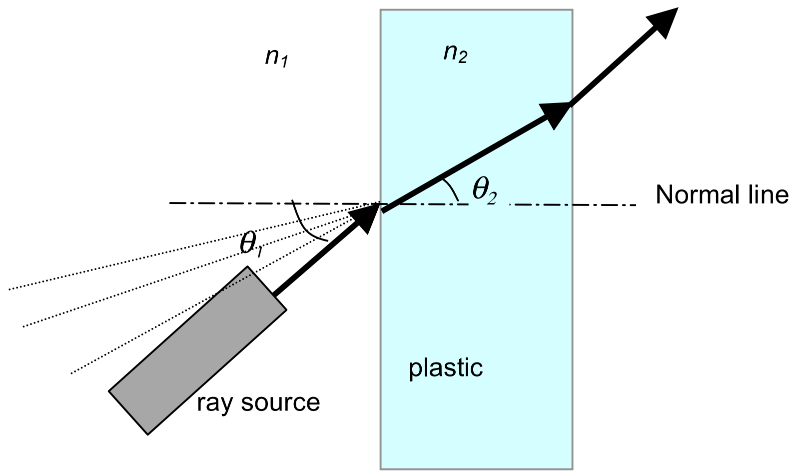


Figure 2—Experimental Set-up. Align box with graph paper lines

3. Line up the ray box or laser so the incident ray follows the 20^0 line. Mark the point where the light exits the plastic shape. Label the exit point "20^0".

4. Repeat step 3 with the other angles of incidence you drew on the paper. Be sure to label the exit points.

5. Remove the prism and draw the lines showing the refracted ray (from the point of incidence to the exit point on the tank) for each angle. Measure the angles of incidence (θ_1) and refraction (θ_2). Remember to measure from the normal!

Analysis (calculations/observations) :

Use the values of incident and refracted angle to calculate the index of refraction for the plastic shape. Find the average of the five measured values.

Conclusions:

Is your result reasonable? Look up values for the index of refraction of different types of transparent plastic and compare the values you find with the one you measured.

Applications/Explorations:

1. Use the rectangular acrylic box in the PHOTON2 kit to find the index of refraction of liquids such as water or cooking oil. How will you need to modify the procedure of this lab? Do you need to consider the thin plastic wall of the box? Why or why not?
2. Make a general rule about how light bends as it goes from a low index of refraction to a higher index, and from a high index to a lower index.
3. The angle of incidence that results in a 90º angle of refraction is called the *critical angle*, θ_c. It can be found from Snell's law by substituting 90º for the angle of refraction, θ_2, and letting the angle of incidence $\theta_1 = \theta_c$. Total internal reflection explains how light is trapped in an optical fiber, and how it is reflected by a prism.

   When does a critical angle exist? What happens when the angle of incidence is greater than the critical angle?

   Derive the equation for the critical angle for light going from one medium to another. Can you devise a method to measure the critical angle for the plastic in the kit? For water?
4. Index of refraction is very important to 3D graphics, where transparent objects must be rendered realistically. Suppose you have three clear, round glasses on a patterned tablecloth. What will you see looking through a glass filled with water (n=1.33)? Filled with sugar syrup ($n \sim 1.5$)?

Snell's Law
Data/Results

Trial #	Incident angle	Refracted angle	*n*
1			
2			
3			
4			
5			
		average measured *n*=	

Index of refraction for comparison (give the type of plastic, and the source of your data.):

____

My Big Fat Plastic Lens
(Refraction at a Curved Surface and the Lensmakers Formula)

Objectives:

- To explore refraction at a curved surface using Snell's law
- To calculate and verify the focal lengths of lens shapes using the Lensmakers Formula

Equipment:

- Semicircle, convex lens and concave lens shapes from the acrylic shapes kit
- Ruler
- Protractor
- Ray box
- Drawing compass

Theoretical overview:

Snell's law predicts the bending of rays as light travels from one medium to another. If the second medium has curved, rather than flat, surfaces, light may be brought to a focus (converge) or it may be made to diverge (spread. In this lab, you will apply Snell's law to a curved surface to demonstrate the focusing of light rays. Then you will explore refraction as light passes from one curved surface to another, using plastic shapes that approximate the cross section of a lens.

It would be very tedious to apply Snell’s law to many points on the two surfaces of a lens! The Lensmakers' formula provides an easy way to predict the focal length of both converging and diverging lenses that have spherical surfaces. The derivation of this equation makes the simplifying assumption that the lens is "thin", that is, that a ray does not translate in the vertical direction as it passes through the lens. (See Figure 1) A thin lens is often represented by a plane in space where the rays are assumed to bend. No real lens meets this ideal, so the results of the Lensmakers' Formula are approximate.

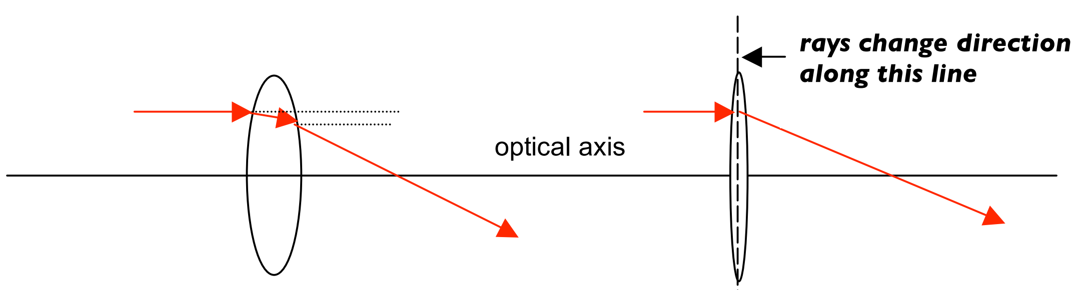


Figure 1 - Real lens (left) and ideal thin lens (right).

The Lensmakers' Formula is derived by applying Snell's law in a general way to spherical surfaces, using the approximation that the incoming rays strike the surfaces at small angles (the paraxial approximation). If

- n is the index of refraction of the lens material,
- R_1 is the radius of curvature of the left hand side of the lens, and
- R_2 is the radius of curvature of the right hand side of the lens, then the focal length of the lens when it is surrounded by air (n=1) is given by:

$$\frac{1}{f} = (n-1)\left(\frac{1}{R_1} - \frac{1}{R_2}\right) \qquad [1] \text{ Lensmakers Formula}$$

To use the Lensmakers Formula, we need a sign convention to distinguish between curvature opening toward the left and toward the right. We will say a curvature is positive if an arrow drawn from the surface to the center of curvature points in the positive direction (to the right) otherwise, it is negative. (See Figure 2) That is, we are using the familiar Cartesian sign convention.

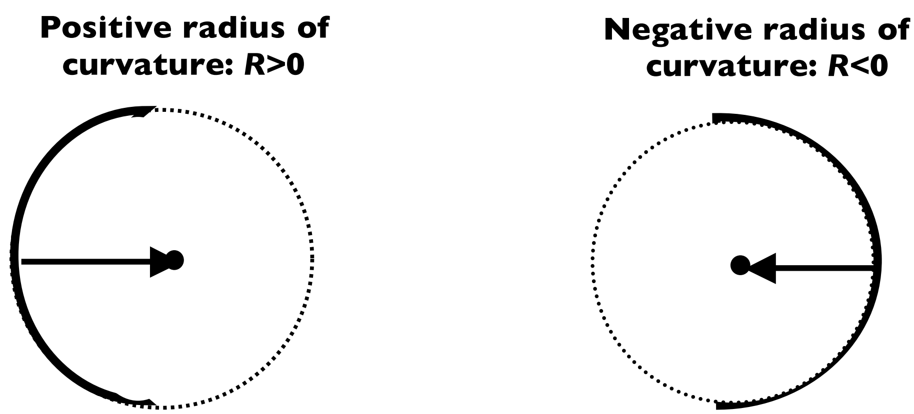


Figure 2. Sign Convention for Spherical Surfaces

In order to perform this experiment, you will need to know the index of refraction of the plastic shapes. If the index of refraction is not given, you need to begin by performing the Snell's Law lab using a flat-sided piece from the plastic prism kit.

Procedure:

1. Refraction at a curved surface by Snell's law
    a. Using the protractor to guide you, carefully draw two perpendicular lines on a piece of paper (See Figure 3) Place the semicircle lens shape on the paper, with the straight side along the vertical line and the optical axis through the center of the lens as shown in the figure. Carefully trace around the shape using a sharp pointed pencil.

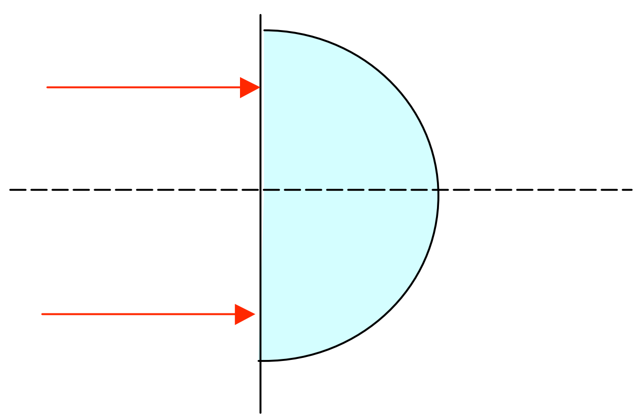


Figure 3- Placement of the plastic half circle

b. Remove the lens shape and measure the distance from the optical axis to the top of the shape. At one half of this distance, draw a line to represent a ray entering the lens from the left, at the flat surface. Be sure the ray is drawn parallel to the optical axis.
c. On the drawing, trace the ray through the first (flat) surface. (Does it bend at this surface?) Trace the ray through the second surface, using the protractor to carefully measure the angle of incidence. (Hint: the radius of a circle strikes the tangent line to the circumference at a right angle. Apply Snell's law to calculate the angle of refraction and draw the refracted ray. Extend the ray until it strikes the optical axis.
d. Repeat steps 2-4 for a ray drawn below the optical axis, as shown in Figure 1.
e. Replace the lens shape on the drawing. Place the ray box so the single ray follows the top ray in the drawing. Mark on the point on the optical axis where the ray crosses. Repeat for the other ray. Measure the distance between the predicted and actual points where the rays meet on the optical axis.

2. Lensmakers Formula
   a. On a new piece of paper, carefully draw two perpendicular lines to serve as the lens axis and the optical axis (See Figure 4) Place the converging lens shape onto the paper, centering it over the axes as shown in the figure. Carefully trace around the shape using a sharp pointed pencil.
   b. Remove the lens and use the compass to find the center of curvature of each of the spherical sides. Use the ruler to measure the radius of curvature for each side of the lens.
   c. Applying the Lensmakers Formula and using the known index of refraction, calculate the focal length of the lens.
   d. To measure the focal length of the lens, return the shape to the piece of paper and place it in the outline previously drawn. Adjust the ray box for the three center rays and direct these toward the lens. Mark the focal point. Remove the lens shape and measure the distance from the lens axis to the focal point to determine the focal length.
   e. Repeat steps 1-4 for the diverging lens shape. To measure the focal length you will need to trace the diverging rays on the right hand side of the lens shape. Remove the lens shape and trace the rays back to the left to find the virtual focal point, as shown in Figure 4 (dashed line).

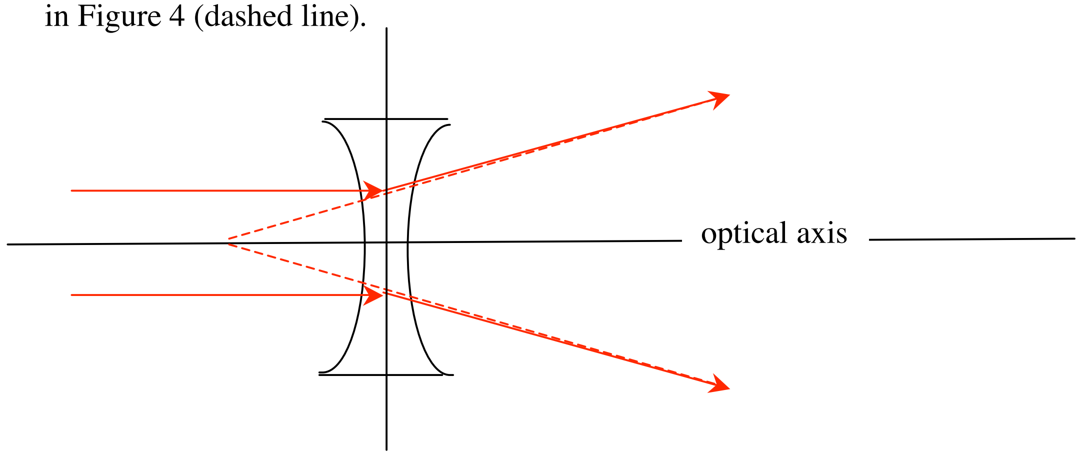


Figure 4 - Finding a virtual focal point

Conclusions/Observations:

How close were your calculated predictions to the experimental results? What do you think were some causes of error in this experiment? Calculate the percent error for the focal lengths for the semicircle and for both lenses. What could you do to improve your results?

Applications/Explorations:

1. The thin lens approximation does not apply very well to the lens shapes in the acrylic shape box. Using the ray box show that the vertical position of a ray changes from one side of the lens to the other. When do you think the thin lens approximation might be a good approximation? When do more exact methods need to be used?
2. Explore spherical aberration. Set the ray box for five rays, and direct all five rays through the flat side of the lens. Do they meet at the same point on the axis? Now turn the lens around so that the rays first strike the curved surface. Which orientation of the lens provides the least spherical aberration? You can see spherical aberration with the convex lens shape by using all five of the ray box rays, rather than just the three used in this experiment. What do you think you could do to minimize spherical aberration in a system using real lenses?

   The Hubble space telescope suffered from spherical aberration when it was first launched, resulting in blurry photos returned to earth. Find out how visiting Space Shuttle astronauts fixed the Hubble telescope at the Hubble's homepage, www.hubblesite.org

Single Lens: The thin lens equation

Objectives:

- To set up a simple lens system and measure and observe image location, size and type as the object distance changes.
- To use the thin lens equation to predict the location, type and size of images produced by a thin lens.

Equipment/Supplies:

All components will be mounted on the breadboard base. You will need:

- A lens with f=10 cm
- Ray box mounted on tilt table
- Cardboard or index card to use as a screen
- (1) 2" post
- (1) 2" post holder
- (1) 3" post
- (1) 3" post holder
- (1) Base plate to simplify lens movement

Theoretical overview

The thin lens equation relates object and image distances to the focal length of a lens:

$$\frac{1}{d_o} + \frac{1}{f} = \frac{1}{d_i}$$

where d_o is the distance from the object to the lens, d_i is the distance from the lens to the image, and f is the focal length of the lens. This equation is useful to determine approximate image distances, but it is important to remember that it is only an approximation.

The sign convention that we are using specifies the lens as the "zero" of the horizontal (x) axis. Thus, measurements made from the lens toward the left are negative and those from the lens toward the right are positive. With this sign convention, the object distance in Figure 1 is negative (it is measured from the lens toward the left) and the image distance is positive. That is, if the object in the figure is 20 cm from the lens, then d_o = -20 cm. If the image forms 30 cm to the right of the lens, d_i = +30 cm.

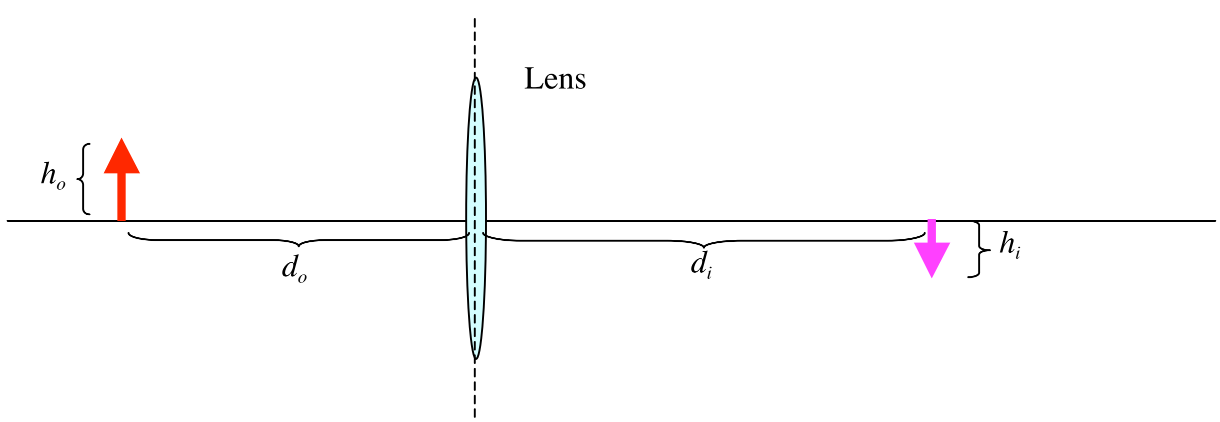


Figure 1: Experimental Set up

The lens that you will use in this lab is a converging lens, so it has a positive focal length. It's important to carefully follow the sign convention and to pay attention to the signs as you do the algebra!

If the object distance and focal length of the lens are known, the image distance can be calculated from the thin lens equation. The transverse magnification is given by

$$M = \frac{d_i}{d_o}$$

so you can calculate the expected magnification of the image. Again, it is important to pay attention to the signs: a negative magnification indicated that the orientation of the image is inverted from that of the object (as shown in the diagram).

The height of the image is then given by

$$h_i = Mh_o$$

where h_i is the height of the image and h_o is the height of the object.

Procedure:

1. Measure and record the size (height) of the object.
2. Predict the size and location of the image for each lens for the following object locations: 30 cm, 25 cm, 20 cm, 15 cm, 5 cm, 1 cm
3. Check your predictions by setting up the object-lens-image system shown above with each of the object distances in the list. Measure the image distance and image height.
4. If the image is virtual (negative image distance) look through the lens and observe the size and apparent location. On the results page, describe whether the image is larger or smaller than the object, and if it appears closer or farther away.

Calculations/Observations/Analysis:

1. Compare your measurements to the expected values by computing % error.

$$\%error = \left(\frac{measured - theoretical}{theoretical} \right) * 100$$

2. What do you notice about the image location as the object moves toward the lens from beyond the focal point, crossing through the focal point, and ending near the lens?
3. What do you notice about the image size as the object moves toward the lens from beyond the focal point, crossing through the focal point, and ending near the lens?
4. What would happen if the object were placed at the focal plane of the lens?
5. Describe the image formed when the object is placed at twice the focal length from the lens. Where does the image form?
6. Suppose an object and lens were placed so that a real image formed on a screen on the other side of the lens. If an opaque piece of cardboard is used to cover the top half of the lens, what change occurs in the image? What if the lens is covered so that only a small hole in the center is exposed?

Conclusions:

Did your results agree with the predictions of the thin lens equation? Why or why not? What specific change could you make in the experiment to improve the results?

Applications/Explorations:

1. The power of a lens changes when the lens is placed in a medium other than air. Explore the change in focal length of a converging lens when it is used in water. How does this explain how swimming goggles help you see more clearly?
2. Hyperopia, or farsightedness, is the condition where the eye can't properly focus n nearby objects. The image formed by the eye's focusing system falls *behind* the retina, because of a cornea that is too flat or an eyeball that is too short. (A related condition, presbyopia, occurs as the eye ages and the lens is no longer able to accommodate, that is, to focus on nearby objects.) Lenses to correct for hyperopia (or presbyopia) take an object at "comfortable" reading distance, usually around 25 cm, and form a virtual image at the closest point the eye can see clearly (called the "near point"). Determine the power of corrective lenses needed by a person who would like to hold a printed page 25 cm from his eyes but is unable to focus on anything closer than 1.25 meters. What kind of lens is this?
3. Can you devise a method to measure the size and image distance for a virtual image?

Single Lens: The Thin Lens Equation
Data/Results

Object height________________

For virtual image, describe the image distance and height as indicated in the procedure.

	Predicted	Measured	% Error
Object distance	30 cm		
Image distance			
Image Height			
Object distance	25 cm		
Image distance			
Image Height			
Object distance	20 cm		
Image distance			
Image Height			
Object distance	15 cm		
Image distance			
Image Height			
Object distance	5 cm		
Image distance			
Image Height			
Object distance	1 cm		
Image distance			
Image Height			

Systems of Two Lenses

Objectives:

- To use the thin lens equation to predict the location, type and size of images produced by systems of two thin lenses
- To set up two lens systems and measure and observe image location, size and type as the object distance changes
- To gain experience with calculations involving virtual objects

Equipment/Supplies:

All components will be mounted on the breadboard base. You will need:

- Two lenses, f_1=15 cm and f_2=10 cm, and two lens holders (If these focal lengths are not available, ask your instructor how far apart to place the lenses.)
- Ray box on a tilt table
- Cardboard or index card to use as screen
- (2) 3" posts
- (2) 3" post holders
- (1) 2" post
- (1) 2" post holder
- (1) base plate to mount moveable lens (lens 2)
- Meter stick and a small ruler

Theoretical overview:

When an image is formed by a system of lenses, several methods may be used to determine the final image size and location. The most straightforward method considers the image formed by the first lens to be the object of the second lens, and so on. In Figure 1, the first lens forms a real image, which then acts as the object for the second lens. Here, the object of the second lens is beyond the focal point of the second lens because the second lens forms a real image, which is the final image for the system.

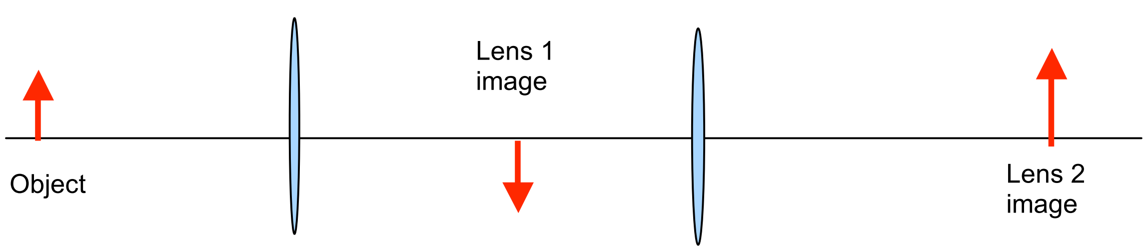


Figure 1 - Example of an image formed by a system of two lenses

As a first approximation, the thin lens equation can be used to find the image location for each lens:

$$\frac{1}{d_o}+\frac{1}{f}=\frac{1}{d_i}$$

The magnification of the lens system is calculated from the magnification of each separate lens.

$$M_{system} = M_1 M_2$$

where

$$M = \frac{d_i}{d_o}$$

for each lens.

The trick is to find the object distance for the second lens. It is important to make a careful, labeled sketch showing both lenses and the image formed by the first lens. In this way, you can easily calculate the distance to the second lens. Note that the image can form beyond the focal point of the second lens (as in Figure 1) or it can form between the focal point of lens 2 and the lens itself. In some cases, the second lens is positioned *before* the location of the first lens image. That is, the image (the object for lens two) is on the *right hand side* of lens two. In this case the object distance is positive, because the object is to the right of the lens, and it is termed a "virtual object."

In this lab, you will observe what happens to the final image as the distance between the two lenses becomes smaller. Note especially how the character and orientation of the final image changes as the lenses move closer together.

Procedure:

1. Measure and record the size (height) of the object.
2. (Optional) Verify the focal length of each of the lenses by the object-image method. For three different object distances (d_o), measure the image distance (d_i). Calculate the focal length of the lens for each trial using the thin lens equation. Find the average focal length.
3. Place the ray box object at a 30 cm from the 15 cm focal length lens (Lens 1). Record the image distance. This distance will not change as the experiment progresses.
4. Set up the following systems of two lenses. Note that only the position of the second lens changes.
   - SYSTEM I (Figure 2) Place Lens 2 (10 cm focal length) 45 cm to the right of Lens 1. Record the location and orientation of the final image. Measure the image height, and calculate the final magnification.

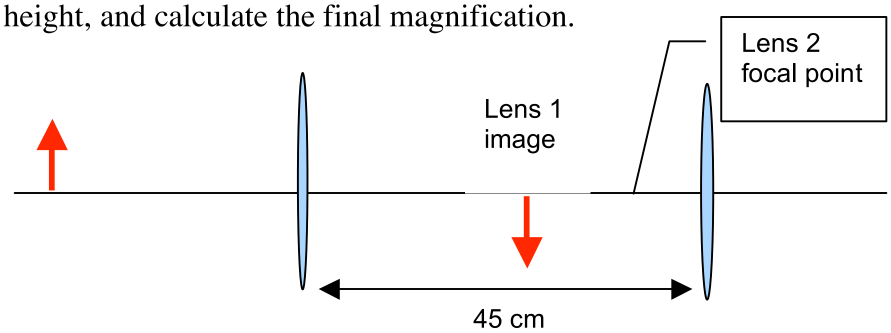


Figure 2 - Object of Lens 2 is beyond the focal point.

   - SYSTEM II (Figure 3): Move Lens 2 so that it is 35 cm from Lens 1.Verify that there is no real image. Look *through* the lenses toward the object. Record the image type and orientation and the estimate the size of the image with respect to the original object. (Can you think of a way to *measure* image distance and size?).

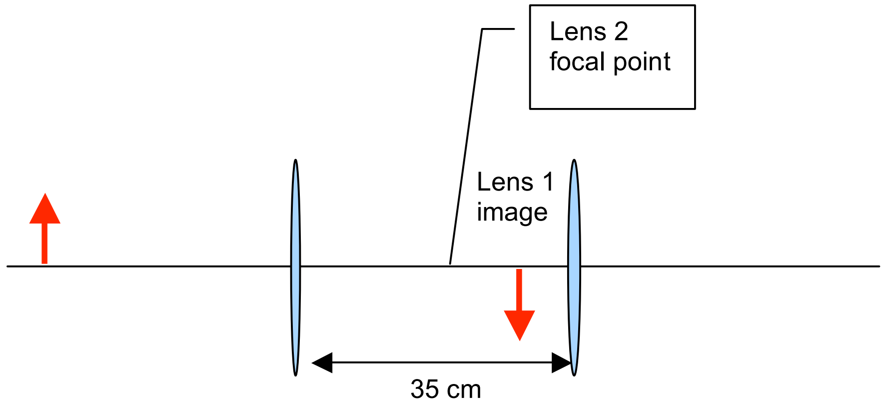


Figure 3 - Lens system II. Object of Lens 2 is between the focal point and Lens 2.

- SYSTEM III (Figure 4): Move Lens 2 until it is 5 cm to the right of Lens 1. Record the location and orientation of the final image. Measure its height, and calculate the final magnification

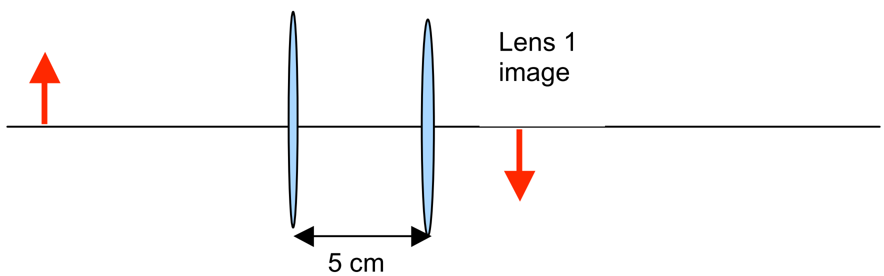


Figure 4 - Lens system III. Object of Lens 2 is virtual (it forms on the right side of Lens 2.)

Analysis (calculations/observations) :

1. For each of the three lens systems, use the initial object distance (for lens 1), the focal lengths of the two lenses, and the distance between the two lenses to calculate the position and magnification of the final image.
2. For Lens Systems I and III, compare your measurements to the expected values by computing % error.

$$\%error = \left(\frac{measured - theoretical}{theoretical} \right) * 100$$

3. For Lens System II, compare your estimates of image size and location to the values you calculated.
4. Describe the character and orientation of the image formed in each of the three lens systems.

Conclusion:

Did your results agree with the predictions of the thin lens equation? Why or why not?

Applications/Explorations:

An astronomical telescope is used to view objects at a large distance, so the incoming rays can be considered to be parallel. (Figure 5) Light enters an objective lens, which forms a real image near or at its focal point. The image is examined by the eye lens, which, in an expensive telescope, may consist of several lenses forming an eyepiece. The eye lens acts as a magnifier to produce a greatly enlarged virtual image of the object.

Usually, the focal points of the objective and eye lens are made to coincide; then the relaxed eye sees the final image at infinity. In this case, the length of the telescope is approximately the sum of the focal points, f_0 and f_e.

Show that the angular magnification of the telescope is given by
Find the angular magnification and the approximate length of the Yerkes Observatory telescope

$$M = \frac{\tan\theta_o}{\tan\theta_e} = \frac{f_o}{f_e}$$

in Wisconsin, which has an objective focal length of 19 meters and an eye lens focal length of 10 cm. What will be the angular separation of the image of two points that are separated by 0.1° of arc in the sky? Will stars appear larger with this telescope than they do with the naked eye?

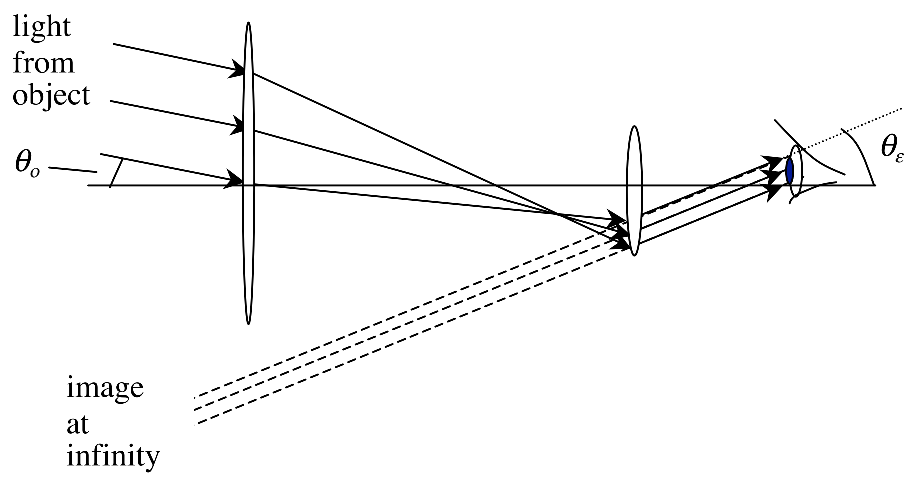


Figure 5 - an astronomical telescope

Systems of Two Lenses

Data/Results

Object height________________

Determination of focal lengths for the two lenses (optional)

Lens 1:

d_o	d_i	f

average focal length= ____________________

Lens 2:

d_o	d_i	f

average focal length= ____________________

Lens Systems

(d_{o1} and d_{i1} are the same for all lens systems)

d_{o1} (object to lens 1)__________________

d_{i1}(lens 1 to first image)_______________

<u>System I</u> ***x*** (distance between lenses)_________________

description of image____

d_{i2} (lens 2 to final image) (exp)____________(calc)___________(% error)___

h_{i2} (final image) (exp)____________

M (system) (exp)____________(calc)___________(% error)___

<u>System II</u> ***x*** (distance between lenses)_________________

description of image____

<u>System III</u> ***x***(distance between lenses)_____________________

description of image____

d_{i2} (lens 2 to final image) (exp)____________(calc)___________(% error)___

h_{i2} (final image) (exp)____________

M (system) (exp)____________(calc)___________(% error)___

Laser Beam Collimation

Safety Notes:

Do not look directly into the laser cavity, or at any reflections of the laser caused by shiny surfaces. Keep beam at bench level so as not to shine the beam accidentally into the eyes of another person.

Objective:

- To expand and collimate a laser beam using the "Keplerian" method

Equipment/Supplies:

- All components will be mounted securely on the breadboard
- HeNe Laser on tilt table
- Lens 1: $f_1 = 8$ mm microscope objective lens in microscope objective holder
- Lens 2: $f_2 = 25$cm biconvex lens
- (3) 3" posts
- (3) 3" post holders
- 2" post
- 2" post holder
- Base plates
- 2"x3" Plane mirror, carefully mounted in a plate holder

Theoretical overview:

Laser beams are typically very narrow in size and they diverge very slowly. A laser pointer, for example, can be used to generate a small spot of light at a great distance. In many applications, such as laser range finding, interferometry, and imaging, a larger beam is more desirable. A larger diameter beam will actually diverge more slowly than a small diameter beam, allowing it to travel farther with less spreading. Laser beam collimation involves the use of two lenses: one to expand the beam to the desired diameter, and one to collect and collimate (make parallel) the beam. The distance between the two lenses is equal to the sum of the two focal lengths.

The two most popular types of beam expanders are the "Keplerian" and the "Galilean." The Keplerian beam expander uses two positive focal length lenses separated by a distance equal to the sum of their focal lengths. The input lens is of shorter focal length than the output lens. The Galilean beam expander uses a negative focal length input lens and a positive output lens separated by a distance equal to the sum of their focal lengths.

In Figure 1, d_1 is the input beam diameter and d_2 is the diameter of the output beam. For either type of expander, it can be shown that:

$$\frac{f_1}{f_2} = \frac{d_1}{d_2} \qquad [1]$$

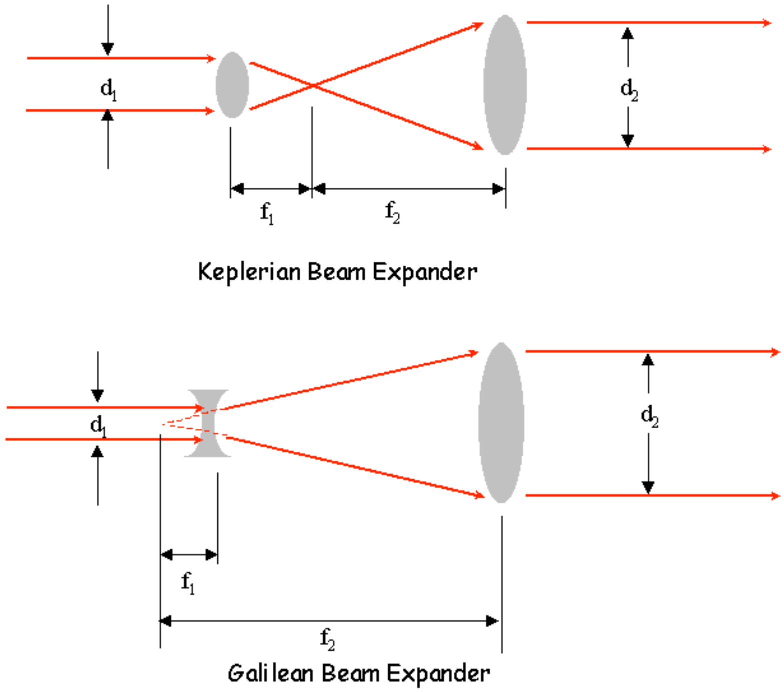


Figure 1 - Beam Expanders

As illustrated in Figure 1, a combination of lenses can always be chosen to fulfill particular divergence or expansion requirements. Note that the above equation will hold only if the F/# ("f-number") of the output lens is equal to the F/# of the input lens where, F/# is given by:

$$F/\# = \frac{f}{D} \qquad [2]$$

In this equation, *f* is the lens focal length and *D* is its diameter. If the beam diameter, *d*, is smaller than the diameter of the lens, then the beam diameter is used in the f/# equation.

Procedure:

1. Secure the laser at one end of the breadboard with the 2" post and post holder (Figure 2).
2. Align the laser beam to a row of holes along the breadboard. Make sure the beam is level (that is, the height above the breadboard is constant).
3. Mount the objective lens (L_l) in a holder and place the post holder on a base plate. Put the lens in the path of the laser. Carefully align the lens so the beam is in the center of the lens.

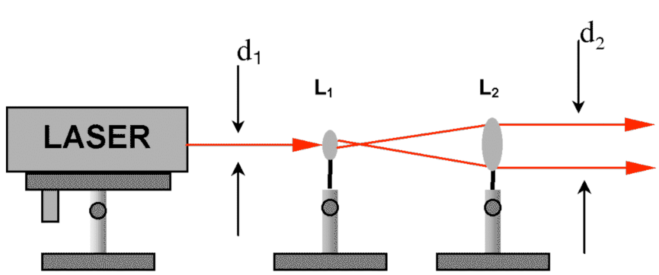


Figure 2- Beam expander lab set-up

4. Mount the 25 cm focal length lens in a holder, also on a base plate, and place it at a distance equal to the sum of the two focal lengths away from the first lens.
5. Note that the exact focal lengths of these lenses are unknown. Therefore, the correct separation for a properly expanded and collimated beam must be found by experimentation using the method that follows, called "autocollimation."
   - Adjust the second lens (roughly) so that the laser beam appears to be collimated, that is, the beam diameter remains roughly constant along the beam.
   - Place the mirror (slightly tilted) in the path of the output beam so that the beam retraces its path.
   - Place an index card slightly off axis at the focal point of the objective lens as shown in Figure 3.

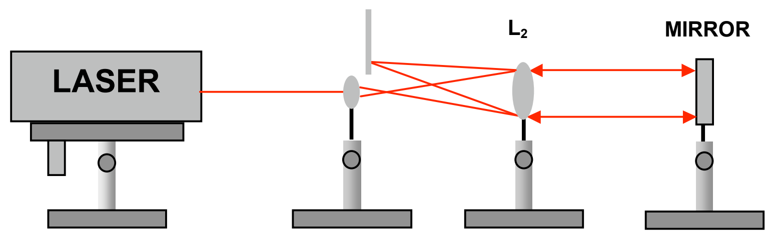


Figure 3 - Autocollimation

   - Adjust the position of the second lens so that the reflected beam comes to focus at the position of the index card. At this point, the beam should be roughly collimated.
   - Remove the mirror from the beam path. Slowly move the second lens along the bench until the expanded beam has relatively the same diameter at a point close to the second lens as a point several meters from the second lens. Check the beam diameter by intercepting the beam with an index card at several locations along the beam.
6. Measure and record the diameters d_1 and d_2 (see Figure 2) of the input and output beams.

Analysis/Calculations:

Calculate the ratios f_1/f_2. and d_1/d_2. Remember that if the beam does not fill the lens, the beam diameter is used. Compare the two ratios and compare your results to the prediction of the Equation (1) for a beam expander. Explain any discrepancies.

Conclusion:

What do you think is the largest source of error in this experiment? How could you minimize this error source?
Why might you need to expand a laser beam? Why might you need a collimated beam? How did you know that the beam was collimated in step 10 of the procedure?

Applications/Explorations:

1. Why might you use a Galilean expander rather than a Keplerian expander? Show that Equation [1] is correct for both types of expander.
2. The divergence (amount of “spreading out”) of a laser beam is given by:

$$\theta = 1.27\ \lambda/d$$

where θ is measured in radians, λ is the wavelength, and d is the diameter of the beam. If a ruby laser (λ = 694 nm) is pointed at the moon, how large a spot will be projected if the laser beam diameter is (a) 2mm (b) 25 cm? Assume the moon is 250,000 miles away.

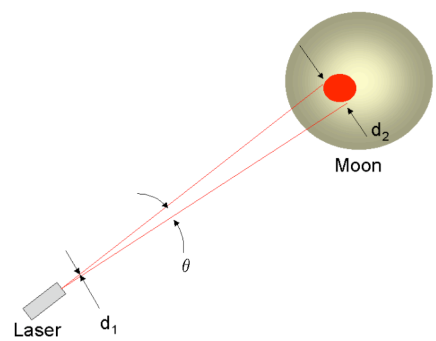


Figure 4 – Laser beam directed from Earth to the Moon

The Apollo 11 astronauts (as well as Apollo 14 and 15) left retroreflectors on the moon that are still used for Lunar Laser Ranging. See the web site http://funphysics.jpl.nasa.gov/technical/grp/lunar-laser.html to learn more

Focal Length of a Negative Lens

Objectives:

- To measure the focal length of a negative lens.
- To gain experience with the use of "virtual objects"

Equipment/Supplies:

All components will be mounted on the breadboard base. You will need:

- Two lenses, f=+10 cm and f=-20 cm, and two lens holders
- Ray box on a tilt table
- Cardboard or index card to use as screen
- (2) 3" posts
- (2) 3" post holders
- (1) 2" post
- (1) 2" post holder
- Meter stick
- Negative lens of unknown focal length

Theoretical overview:

How can you find the focal length of a diverging (negative) lens? The focal length of a positive lens is easily approximated by allowing light from a very distant object to form an image on a screen. The distance from the lens to the screen is the focal length of the lens. The focal length of a negative lens cannot be measured directly in the same way. (Why?)

One method for measuring the focal length of a negative lens is to use a converging lens to form an image and then to measure the shift of the image when the negative lens is inserted. (See Figure 1.) That is, the image formed by Lens 1 (at screen position 1) is the object for Lens 2. This object is termed "virtual" because it never actually forms, since Lens 2 is "in the way." The focal length of Lens 1 is not important. Its only function is to provide an image to act as the object for the negative lens, Lens 2.

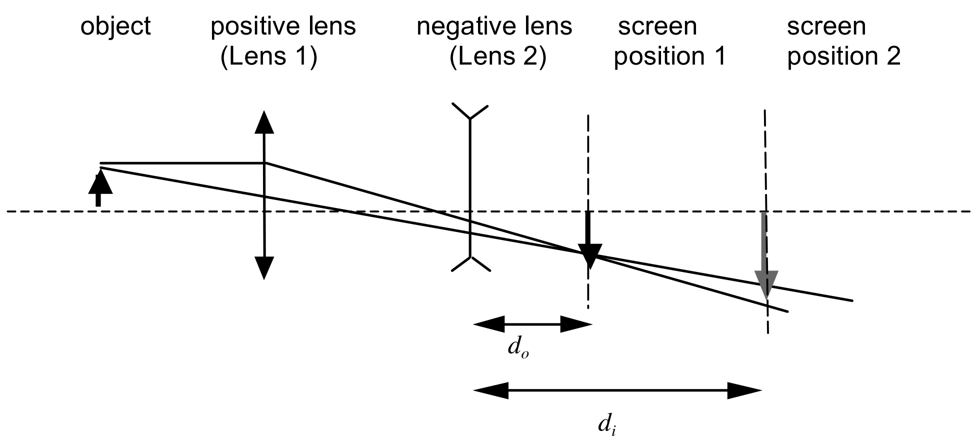


Figure 1 – Geometry of the experiment. The rays show the position of the real image formed by Lens 1. Note that the object for Lens 2 is to the *right* of the lens, not to the left as is the usual case.

In Figure 1, the positive lens creates an image that can be viewed by placing a screen at position 1. Next, the negative lens is placed between the converging lens and the image, as shown in the figure. The negative lens causes the rays forming the image to diverge (or, to converge more slowly) and the image moves out to screen position 2. The distances from the lens to screen position 1 (the virtual object) and to screen position 2 (Lens 2 image) are the object and image distance, respectively, for Lens 2. The thin lens equation can then be used to find the focal length of Lens 2.

Procedure:

Part 1. Ray diagram simulation

Although this part of the procedure is optional, it is very helpful to see the ray diagram for this lab, and to observe how changing the lens positions affects the final image location and size.

1. **Go to http://www.hazelwood.k12.mo.us/~grichert/optics/intro.html**
2. Click on the word "object" and click and drag an object at the left edge of the optical bench (the yellow line.) The object size is unimportant, but a height of around y=0.4 units works well. Note that there are no length units; we'll just call them "units." The x and y dimensions are found in a small rectangle at the lower left of the screen.
3. Click on the word "lens" and and then click again to place the lens on the optical bench. Change the lens focal length to 0.8 units by dragging the focal point and place the lens at about 1.25 units from the object. (Drag the entire lens.) The ray diagram will be drawn showing a large, inverted, real image on the right side of the bench. Move the lens around a bit to see what happens!
4. Now create the negative lens. First, click "lens" and create a positive lens to the optical bench. To make a diverging lens, grab one of the focal points and drag it *through* the lens. You will see the shape of the lens change. Make the focal length -1.7 units.
5. Move the negative lens to a point between the positive lens and the original image so that a new image is formed near the right edge of the bench.
6. Record the object and image distances for the negative lens on the simulation and calculate the focal length, f. Compare to the value of the negative lens' focal length (-1.7 units)

Part 2. Lab procedure

1. Set up the ray box (arrow object) and a 10 cm converging lens. Mark the location of the image (screen position 1) on the breadboard.
2. Place a -20 cm lens between Lens 1 and screen position 1 and find the new image location (screen position 2.) Measure the object and image distance for Lens 2.
3. Repeat using a diverging lens of "unknown" focal length.

Analysis/Calculations;

Calculate the focal length for Lens 2 and for the unknown lens. (Hint: What is the sign for the object distance?) For the known focal length, calculate the percent error from the known value.

Conclusions:

How well did your result correspond to the known focal length? What could you do to improve your results?

Applications/Explorations:

Myopia, or nearsightedness, occurs when an eye can't focus properly on very distant objects. The image formed by the myopic eye's focusing system falls *in front of* the retina- either the cornea is too curved, or the eyeball itself is too long (or a combination of the two). Lenses to correct for myopia take an object at a very large distance and form a virtual image of the object at the farthest point a person can see clearly (called the "far point"). Suppose a person wants to see very distant objects clearly, but her far point is only 40 cm. What power lens is required? Are the lenses converging or diverging? Draw a lens diagram to show how myopic vision is corrected with a lens.

Focal Length of a Negative Lens
Data/Results

1. Web applet simulation

d_o	
d_i	
f measured from computer screen	
f (known value)	
% error	

2. Lab experiment
Lens with known focal length

d_o	
d_i	
f (calculated from thin lens equation)	
f (known value)	
% error	

Lens with unknown focal length

d_o	
d_i	
f (calculated from thin lens equation)	

Focal Length of a Spherical Mirror

Objective:

- To measure the focal lengths of concave and convex spherical mirrors

Equipment/Supplies:

- Ray box light source on a tilt table
- 10 cm focal length lens in a lens holder
- Concave spherical mirror (mount in a bar-type lens holder on a moveable base plate)
- Convex spherical mirror (mount in a bar-type lens holder on a moveable base plate)
- Cardboard to use a screen
- (2) 3" posts
- (2) 3" post holders
- (1) 2" post
- (1) 2" post holder
- Meter stick

Theoretical overview:

The focal length of a concave mirror can be easily found using the techniques we used for a thin converging lens. Since the mirror forms a real image when the object is outside of the focal point, object and image distances are readily measured.

A convex lens presents a different situation. Since it cannot form a real image, we must use a different technique to measure its focal length. In this lab, we use a lens to form a real image, which is then the object for the concave spherical mirror. This technique is necessary, since it is the only way to place an image at the center of curvature, behind the mirror.

For a concave (converging) mirror, if the object is located at the center of curvature of the mirror ($d_o = -R$), the image distance is found from the mirror equation, where $f = R/2$:

$$\frac{1}{d_o} + \frac{1}{f} = \frac{1}{d_i}$$

$$\frac{1}{-R} + \frac{2}{R} = \frac{1}{d_i}$$

Solving for image distance,

$$d_i = R$$

That is, the image is located at the same position as the object, at the center of curvature of the mirror. (See Figure 1.)

For the convex (diverging) mirror, a lens is used to produce a *virtual object*, that is, an object to the *right* of the mirror, at the center of curvature. (See Figure 2) Again, when the object distance is equal to the radius of curvature of the mirror, the image distance is also equal to the radius of curvature of the mirror. In the mirror equation above, the focal length is negative (because it is a convex mirror) but the object distance is positive (it is on the "wrong" side of the mirror for an object). You can check to see that the image distance will be -R, that is, a virtual image forms at the location of the virtual object behind the mirror.

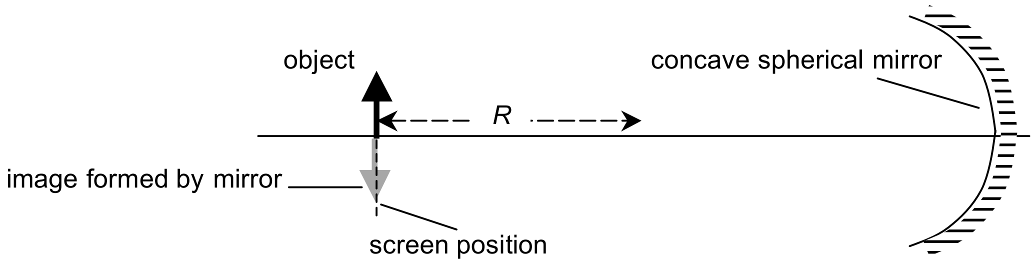


Figure 1 - Concave mirror. When the object is at the center of curvature of the mirror, the image forms at the same location. The screen must not block the light from the object to the mirror! It helps to tilt the mirror slightly to one side.

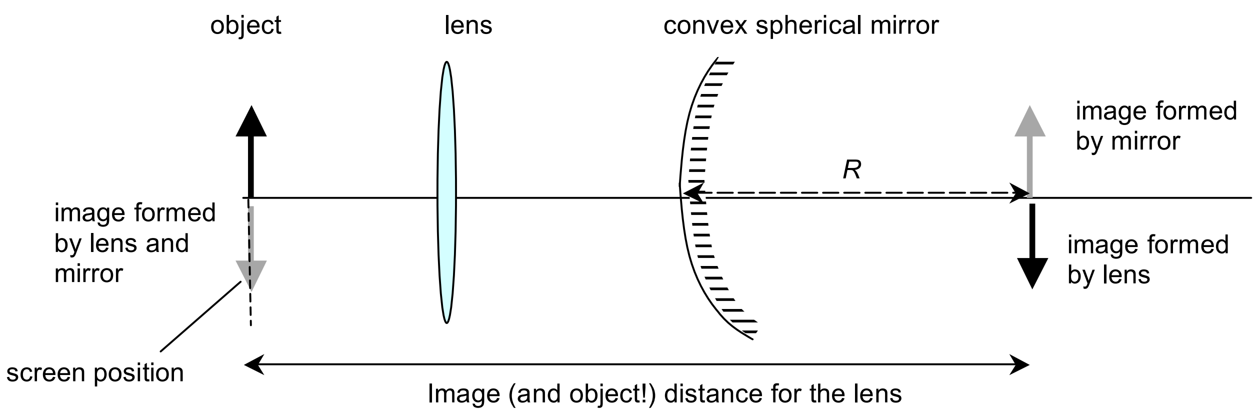


Figure 2 - Convex mirror. The lens forms an image behind the mirror. If the image is at the mirror's center of curvature, the mirror forms a virtual image at the same location. This virtual image is then the object for the lens, which forms a real image at the location of the original object.

The difficulty with the convex mirror is that its image is difficult to see (the lens is in the way) and since it is a virtual image, the image distance is difficult to measure. However, when the object, lens and mirror are in the correct orientation to provide the situation shown in Figure 2, a third image forms directly under the original object. This image is formed by the lens, acting on the light reflected by the mirror. Since the original lens image distance (from lens to image on the right in Figure 2) is now the lens object distance, the final image forms at the location of the original object. It is this image that you will observe.

Procedure:

Part 1. Ray diagram simulation

Although this part of the procedure is optional, it is very helpful to see the ray diagram for this lab, and to observe how changing the lens and positions affect the final image location and size.

1. **Go to http://www.hazelwood.k12.mo.us/~grichert/optics/intro.html**
2. Click on the word "object" and click and drag an object at the left edge of the optical bench (the yellow line.) The object size is unimportant, but a height of around *y*=0.4 units

works well. Note that there are no length units; we'll just call them "units." The *x* and *y* dimensions are found in a small rectangle at the lower left of the screen.

3. Concave mirror. Choose a mirror and place it to the right of the object. Create a 1.0 unit focal length for the mirror by clicking and dragging on one of its focal points. Move the mirror until you find the location where the mirror forms an image directly beneath the object. The distance from the image to the mirror surface is *R*, the radius of curvature of the mirror. Use the applet cursor and the coordinates shown in the lower left of the screen to measure *R*. Verify that the radius is twice the focal length.
4. Convex mirror. Remove the concave mirror. Choose a lens and place it in the center of the applet screen. (Click on the lens button at the bottom of the applet screen, then click in the center of the screen.) Adjust the lens focal length by clicking and dragging on one of the focal points until the lens has about a 0.8 unit focal length. Note that a real image, labeled "1" forms to the right of the lens. Move the lens until the image is about 2.5 units from the lens. (Use the cursor and coordinates to place the lens.) The image should form at about the center of the screen.
5. Add a spherical mirror and adjust the mirror to produce a convex mirror with a (-)1.0 unit focal length. To do this, drag the focal point *through* the mirror to the opposite side. Slide the mirror toward the lens until the image formed by the mirror (labeled "2") is directly above the image formed by the lens (labeled "1"). The distance from the image to the mirror surface is *R*. Use the applet cursor and the coordinates shown in the lower left of the screen to measure *R*. Verify that the radius is twice the focal length.
6. Notice that the rays leaving the mirror and passing through the lens toward the left meet to form a real image directly under the position of the original object. This is the image you will view in the experiment.

Part 2. Experiment

1. Concave mirror: Set up the situation shown in Figure 1 for the concave mirror. Place a concave front surface mirror to the right of the ray box target and an index card or other screen just below the ray box. Adjust the mirror position until the image is sharply focused on the card. You may need to tilt the mirror slightly downward. Measure and record the distance object to the front surface of the mirror, which is the radius of curvature.
2. Concave mirror check: Choose a very distant object, such as a tree or building outdoors, and measure the image distance for this "infinitely distant" object.
3. Set up the situation shown in Figure 2 for the convex mirror. Use a 10 cm lens and the ray box target to form the first image. Note the location of this image. Place a convex front surface mirror to the right of the lens and adjust the mirror position until the image formed by the lens and the mirror forms directly below the object. Measure and record the distance from the front surface of the mirror to the location of the image formed by the lens.

Analysis (calculations/observations):

Compute the focal length for each mirror. For the concave mirror, compute the percent difference between the values obtained by the two different methods. If the mirror focal lengths are available, compute the percent error for each mirror.

Conclusion:

How did your measured values compare to the known value? How could you improve upon the results of this experiment?

Applications/Explorations:

Concave and convex mirrors can be found in a number of applications: make-up mirrors, surveillance mirrors in convenience stores, the passenger side rear view mirror on a car, and reflecting telescopes, including the Hubble telescope. For each of these applications, which type of mirror is used, concave or convex? Why is that the mirror of choice? When (and why) are parabolic mirrors used?

Focal Length of a Spherical Mirror
Data/Results

1. Web applet simulation

Concave mirror *R* (measured)	
Concave mirror *f* (known)	
Convex mirror *R* (measured)	
Concave mirror *f* (known)	

2. Lab experiment
Concave mirror

1	measured R	
2	*f* (calculated from *R*)	
3	*f* (measured with distant object)	
4	*f* (known value, if available)	
5	% difference, focal lengths in lines 2 and 3	
6	% error, focal lengths in lines 2 and 4	

Lens with unknown focal length
Concave mirror

1	measured *R*	
2	*f* (calculated from *R*)	
3	*f* (known value, if available)	
4	% error, focal lengths in lines 2 and 3	

Young's Double Slit

Safety Notes

Do not look directly into the laser cavity, or at any reflections of the laser caused by shiny surfaces. Keep beam at bench level so as not to accidentally shine the beam into the eyes of another person.

Objectives:

- To verify the conditions for constructive and destructive interference in Young's double slit experiment
- To use Young's double slit equation to measure the separation of two closely spaced slits

Equipment/Supplies:

- Optical breadboard
- Helium-neon laser on tilt table
- Slide with sets of double slits in bar-type lens holder
- 2" post
- 2" post holder
- 3" post
- 3" post holder

Theoretical overview:

The classic experiment for producing interference is *Young's double-slit* experiment developed by British physicist and physician Thomas Young (1773-1829). By letting light pass through two closely separated narrow slits in an opaque screen, Young found that the pattern formed on a distant screen was caused by the interference of the two light waves emanating from the two slits as shown in Figure 1.

If we consider the light emanating from the two narrow slits as point sources, we can see that the light in the center of the screen has traveled an equal distance from each slit and is therefore in phase, causing constructive interference. The bright fringe formed is called the *zeroth- order maximum*. The path difference Γ in the center is zero. ($\Gamma = 0$)

As we go away from the center point up or down along the screen, the path difference Γ increases until the two waves are 180° out of phase. At this point

$$\Gamma = \lambda/2$$

and a dark fringe or *minimum* occurs. As we continue to go away from the center, the phase difference approaches 360° or

$$\Gamma = \lambda$$

and the first-order bright fringe or maximum is formed. In general, as one moves away from the center of the screen in either direction, a maximum will occur whenever the path difference is equal to a integer multiple of the wavelength, $m\lambda$.

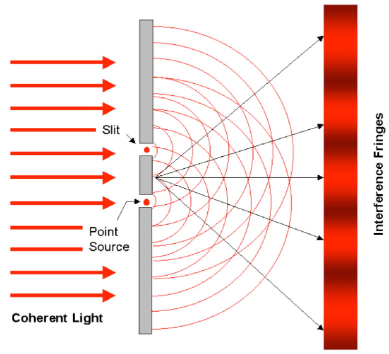


Figure 1 – Young's Double Slit Experiment

Referring to Figure 2, we can show that a maximum appears whenever

$$\Gamma = m\lambda \qquad [1]$$

Also from the figure, we can show that

$$\Gamma = d \sin\theta \qquad [2]$$

Equating Equations [1] and [2] we get

$$d \sin\theta = m\lambda \qquad m = 0,1,2,3..... \quad [3]$$

which is *Young's double slit equation* for calculating the position of an mth order maximum.

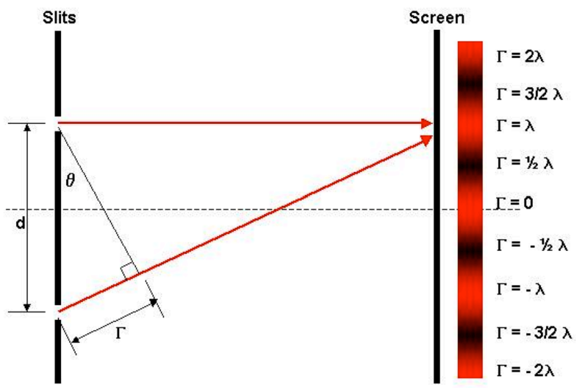


Figure 2 –2 Geometry of Young's Double Slit equation

We can simplify the measurements in this experiment by noting that θ is a very small angle, because the entire pattern on the screen is much less than the distance between the slits and the screen. This allows us to use the small angle approximation,

$$\sin\theta \sim \tan\theta = y/x$$

"y" is the distance along the screen from the center of the pattern to any other point on the pattern, and x is the distance from the two slits to the screen. Then

$$y = m\lambda x/d \qquad m = 0,1,2,3.....$$

predicts the locations of the maxima on the screen.

Procedure:

1. Tape the paper onto a wall and place double slit slide 1 to 2 meters from the wall. Measure and record the distance from the slits to the paper.
2. Pass the laser beam through one set of slits and observe the resulting interference pattern on the paper. Be sure the beam goes through only one set of slits at a time.
3. Carefully mark the centers of the interference maxima on the paper screen.

4. Repeat steps 3 and 4 for another set of double slits at a separate level on the paper.
5. Take the paper down. Measure and record the distance "*y*" from the center of the interference pattern to three orders on either side of the center. Be sure to record the order number corresponding to each distance measurement.
6. Repeat for a second set of slits.

Analysis/Calculations :

Use your experimental data for the locations of the interference maxima and the known wavelength of the laser to calculate the spacing of the slits for each measurement. Find the average slit spacing for each pair of slits you tested. Compare to the known spacing (if available) by calculating percent error.

Conclusion:

Did your results verify Young's Double Slit Equation? Why or why not? How might you change this experiment to improve the results?

Applications/Explorations:

1. The double slit experiment may be used to determine the wavelength of a light source if the slit separation is known. Use the same experimental set up to determine the wavelength of a laser pointer. You can use the double slit to measure the wavelength of a non-laser source as well, but you must be sure that the light is spatially coherent across the two slits. Why is this important?
2. The double slit pattern is not constant brightness, but varies according to the single slit diffraction pattern. That is, the single slit pattern *modulates* the double slit pattern. Use the minima of the single slit pattern to determine the width of the individual slits comprising the pair of slits.

Young's Double Slit
Data/Results

Laser wavelength______________________

Distance from slits to screen___________________

First set of slits:

m	distance to mth maximum from center of pattern (y_m)	calculated distance between slits (d)

Average calculated d _____________________

Known d ___________________

% error __________________

Second set of slits:

m	distance to mth maximum from center of pattern (y_m)	calculated distance between slits (d)

Average calculated d _____________________

Known d ___________________

% error __________________

Diffraction Grating

Safety Notes

Do not look directly into the laser cavity, or at any reflections of the laser caused by shiny surfaces. Keep beam at bench level so as not to accidentally shine the beam into the eyes of another person.

Objectives:

- To determine the wavelength of diffracted light, by means of a transmission grating.

Equipment/Supplies:

- laser on tilt table
- diffraction grating slide mounted in slide holder
- viewing screen
- posts and post holders to mount grating on optical breadboard

Theoretical overview:

A diffraction grating is a device based on Young's double slit principle and, in the same way, it produces interference through diffraction. In Young's double slit experiment, passing light through narrow slits in an opaque screen generates an interference pattern. A diffraction grating, however, has hundreds or even thousands of slits. By increasing the number of effective point sources contributing to the interference pattern, the maxima become very sharp, thus increasing the ability to resolve closely spaced wavelengths.

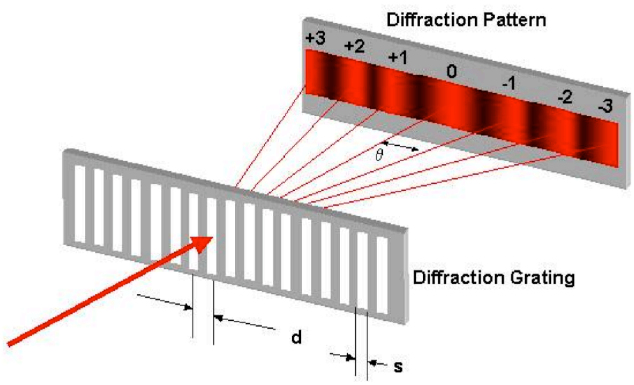


Figure 1 - The Diffraction Grating

Although a diffraction grating is often pictured as parallel slits in an otherwise opaque screen, gratings are usually constructed of a transparent material with closely spaced "grooves." (Figure 1) Early gratings were created by scribing closely spaced lines in the surface of a glass plate with a diamond stylus, but modern gratings are often made by holographic techniques. Both transmission and reflection gratings may be found in instruments used to study the spectra of light sources. In this lab, you will use a transmission grating.

The equation that defines the positions of the maxima for a diffraction grating is the same as that for Young's double slit:

$$d \sin \theta = m\lambda \quad m = 0, 1, 2, 3, ... \quad [1]$$

where d is the separation between two adjacent slits, θ is the angle through which the mth order is diffracted, and λ is the wavelength of the light. Note that d is not usually given; more likely, you will be given the number of grooves per unit length (called lines/cm or lines/mm, for example.)

Unlike the double slit, the diffraction grating produces interference fringes at wide angles, so the small angle approximation may not be used to simplify Equation 1.

Procedure:

1. Set up the laser and grating so that the laser beam is normally incident on the grating. Observe the pattern produced on a screen about one meter from the grating.
2. Measure and record the distance from the grating to the screen.
3. Measure and record the distances to the first, second and third diffraction maxima on both sides of the central maximum.

Analysis (calculations/observations) :

1. For each maximum on either side of the center maximum, calculate the diffraction angle θ using the inverse tangent function.
2. Using the known value of line spacing for your grating, calculate the wavelength of the laser for each maximum measured. Calculate the average wavelength. Compare to the known value by computing percent error.

Conclusions:

Did your results agree with the results of the diffraction grating equation? Why or why not? What would you have observed if you used a shorter wavelength light source? What would you have observed if you used a grating with closer line spacing?

Applications/Explorations:

The grooves on a CD act like a reflection grating. Measure the line spacing of a CD by reflecting laser light from the grooved surface. (Hint: if the laser strikes the CD at right angles, Equation 1 may be used. Otherwise, you need to use a form of the grating equation for light striking at a non-zero angle of incidence.) The area of the CD's pits is approximately $d^2/2$, where d is the groove spacing. How many pits can fit in the usable area of a CD? At 8 bits per byte, approximately how many megabytes can the CD hold? Compare your calculation to the stated CD capacity.

Diffraction Grating
Data/Results

Grating lines/mm___________________

Grating line spacing (*d*)__________________

Distance to screen (*x*)__________________

order (m)	distance to mth max. (y_m)	θ_m	wavelength (measured)

average measured wavelength_______________

known wavelength_____________________

percent error__________________

Michelson Interferometer

Safety Notes

Do not look directly into the laser cavity, or at any reflections of the laser caused by shiny surfaces. Keep beam at bench level so as not to shine the beam accidentally into the eyes of another person.

Objectives:

- To construct and evaluate a Michelson interferometer.

Equipment/Supplies:

- All components are mounted on an optical breadboard:
- HeNe Laser on laser tilt table
- (2) Adjustable Mirrors
- Cube Beam Splitter
- Cube Beam Splitter Mount (horizontal rotational stage)
- 2” Post Holder and Post
- (4) 3” Post Holder and Post
- Index card
- 8 mm Microscope Objective and Mount
- Linear Translation Stage
- 25cm Focal Length Biconvex Lenses (Beam expander/Collimator) (Optional)

Theoretical overview:

The Michelson interferometer is a highly precise optical instrument used to measure small changes in optical path lengths. A typical Michelson interferometer can produce both circular and straight-line fringes. These fringes can be used to make very precise measurements that result from small movements and vibrations, aberrations and/or scratches in optical components, changes in refractive index, and many other applications that require resolution in the order of the wavelength of light.

A simple Michelson interferometer requires a light source with good coherence properties such as a laser, a beam-splitter, and two mirrors as shown in Figure 1. Light from the laser passes through a beam expander (microscope objective) and then through a beam splitter where it is split into two paths: A-B and C-D. Light in path A-B is reflected by the movable mirror and retraces its path to the beam splitter where it is reflected onto the index card. Light in path C-D is reflected by the fixed mirror and travels back through the beam splitter where it is combined with beam A-B.

If the path lengths A-B and C-D are identical, the two beams interfere constructively and form a bright spot. If the movable mirror is moved by 1/4 wavelength, the path difference between the two beams becomes 1/2 wavelength and destructive interference occurs, generating a dark fringe. If the movable mirror is moved by another 1/4 wavelength (for a total of 1/2 wavelength), the path difference between the two beams is one wavelength and constructive interference occurs again. Subsequently, for every additional 1/2 wavelength movement of the mirror, the path difference between the two beams will be an integer multiple of one wavelength generating one bright interference fringe.

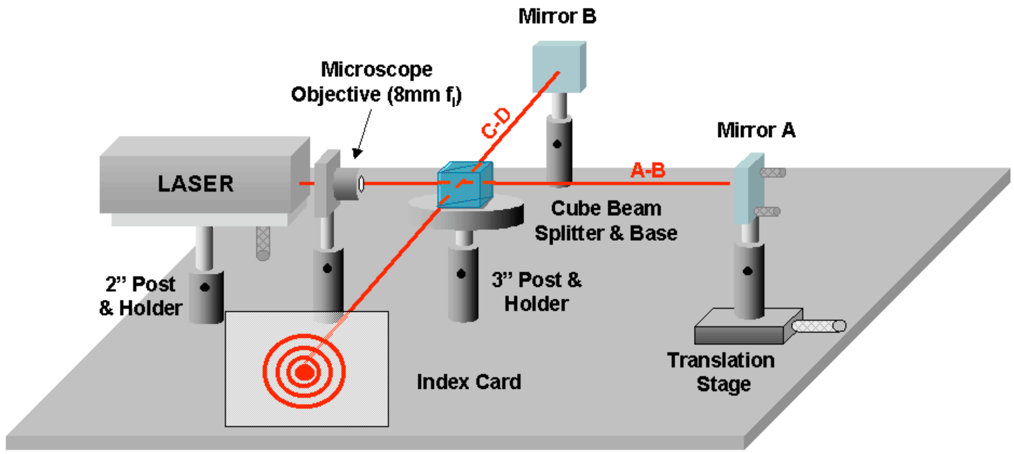


Figure 1-A Michelson interferometer

The interference pattern on the screen resembles a bull's eye, with new fringes emanating from the center (or collapsing into the center if the mirror is moved closer to the beam splitter) for each mirror movement of 1/2 wavelength. The distance the mirror has moved can be calculated simply by:

$$\text{Distance} = \text{\# of fringes generated x } (\lambda/2) \qquad [1]$$

Often it is more convenient to view straight-line fringes for precision measurements. By introducing a small amount of tilt in one of the mirrors, the fringe pattern will change to a series of straight lines. The distance between each line represents 1/2 wavelength of displacement. Any deviation from a straight line can be directly measured. For example, in Figure 2, the $\lambda/4$ deep scratch in one of the mirrors can be determined by measuring the amount of deviation from the straight fringe in terms of λ.

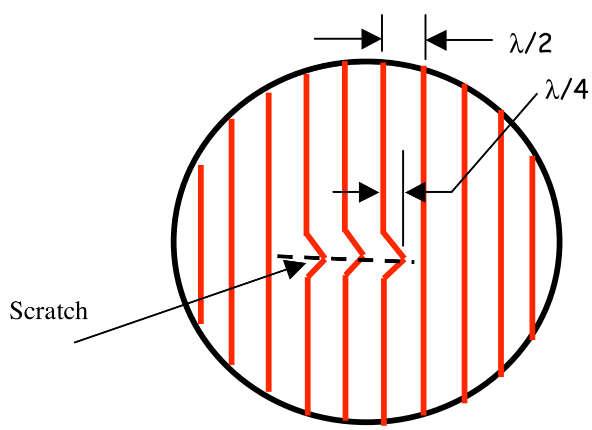


Figure 2 - the distance between straight line fringes represents one half wavelength

Procedure:

1. Mount the laser on the breadboard using the adjustable mount as in Figure 1. Make sure that the mounting post in at its lowest possible level for stability.

2. Align the height of the laser beam with the breadboard. It should be level and straight along a row of holes. This is a critical step- if the laser beam is not straight and level, it will not be possible to align the interferometer.
3. Mount Mirror “A” on the translation stage. Mount the stage on the breadboard to that the mirror is approximately 30 cm from the laser. The laser beam should strike the mirror in the center. Use the mirror adjustments to redirect the laser beam back into the laser. This will assure that the mirror is perpendicular to the beam.
4. Mount the beam splitter on its platform mount in the path of the laser beam. The center of the cube should be approximately 10 cm from the laser. Again, make sure the beam strikes the middle of the cube. Position the cube so that the laser beam’s refection from the front surface goes back into the laser. This will assure that the cube is perpendicular to the beam.
5. Mount Mirror “B” approximately 20 cm from the center of the cube as shown in Figure 1. (The two mirrors should be equidistant from the beam splitter.) The laser beam should strike the mirror in the center. Adjust the mirror so that the laser beam is co-aligned with beam A-B. One trick is to observe the two beams a distant point (across the room) until they overlap. This process may take some patience and a lot of tweaking (this is why optical techs make the big bucks!).
6. Once the two beams are co-aligned, place the microscope objective in the path of the laser beam just beyond the output of the laser to expand the beam. You should see some interference fringes displayed on the index card. If you do not see any fringes, tweak one of the mirrors gently until they appear.
7. Adjust the mirrors so that a bull’s eye pattern is observed (this also takes a good deal of patience).
8. Place your hands above and below the beams in one of the arms of the interferometer to "cup" the beam. Observe what happens to the pattern on the screen. Record your observations.
9. Observe what happens to the fringe pattern as you very slowly move mirror “A” back using the translation stage. What direction do the fringes move? Record your observations.
10. Observe what happens to the fringe pattern if one of the mirrors is slightly tilted.
11. Move the beam expander to the output side of the interferometer, that is, between the beam splitter and the index card. Observe and record the changes to the pattern.

Applications/Explorations:

1. There are many variations on the interferometer you just built. When the light entering the interferometer is collimated, it is called a Twyman-Green interferometer. Michelson himself used an extended source of light. Using the technique learned in the “Laser Beam Collimation” lab, expand and collimate the laser beam to a size of approximately 1 cm by placing a converging lens after the microscope objective (See Figure 3). Repeat steps 3-7 until you obtain approximately 10 straight-line fringes on the index card. Repeat steps 8 and 9 and compare the fringes you see with this form of interferometer to those seen earlier.

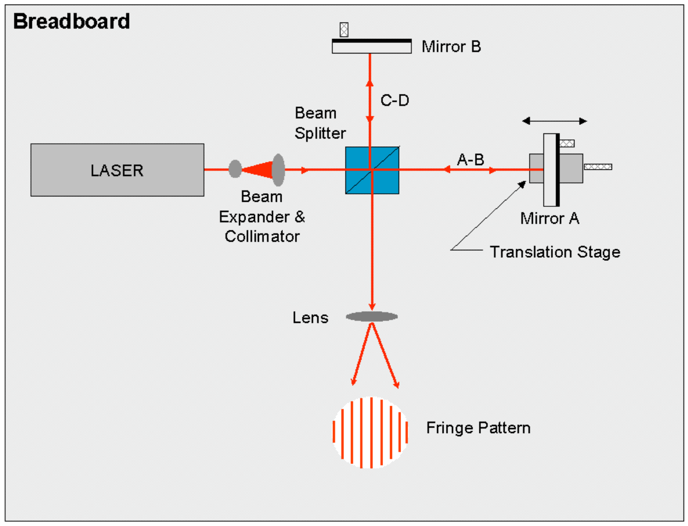


Figure 3

2. Since the number of fringes emanating from the center of the interference pattern depends on the wavelength of the laser light (equation [1]), you should be able to measure the wavelength by moving mirror "A" in Figure 1 a known distance and counting the number of fringes that appear (or disappear) at the center of the pattern. You will need to move the translation stage *very* slowly and smoothly, while counting fringes. Measure the wavelength of the laser light, and calculate the percent error from the known value. How could the interferometer be used to measure small distances moved by, say, a vibrating part?

Michelson Interferometer
Data/Results

1. What happened to the pattern when you put your hands around the beam? What is it about your hands that caused this change? How does this affect the light path in the interferometer?
2. What happened to the fringe pattern as you slowly moved mirror A? If you were unable to decide how the fringes were moving, explain why. What could you do to improve the situation and make the fringes' movement more visible?
3. What did you see when you tilted one of the mirrors? Explain
4. What did you see when the beam expander was moved to between the beam splitter and the index card? When might this be useful?

Air Wedge

Safety Notes

Do not look directly into the laser cavity, or at any reflections of the laser caused by shiny surfaces. Keep beam at bench level so as not to accidentally shine the beam into the eyes of another person.

Objectives:

- To study interference fringes in a wedge-shaped film of air
- To use an air wedge to determine the thickness of a piece of plastic or other thin object

Equipment/Supplies:

- Monochromatic source of light. A laser beam reflected by a mirror wrapped in wax paper works well, or use a short focus concave spherical mirror to expand the beam.
- 2 flat glass plates
- Very thin (50 µm or less) object whose thickness can be known by independent means, for example, a piece of a plastic trash bag of known thickness.

Theoretical overview:

An air wedge is formed by placing two glass plates in contact and inserting something in one end to hold the plates apart. For example, Figure 1 shows an air wedge formed by two narrow glass plates with a hair inserted across one end. The wedge angle in Figure 1 is greatly exaggerated.

On either side of the air wedge, light is reflected from the bottom surface of the top plate and from the top surface of the bottom plate. We will consider light that strikes, and is viewed, perpendicular to the plates. (However, for clarity, the rays are shown striking the surface at a non-zero angle of incidence.) The light that enters the wedge and is reflected from the bottom surface travels an additional distance equal to 2t, where t is the thickness of the wedge.

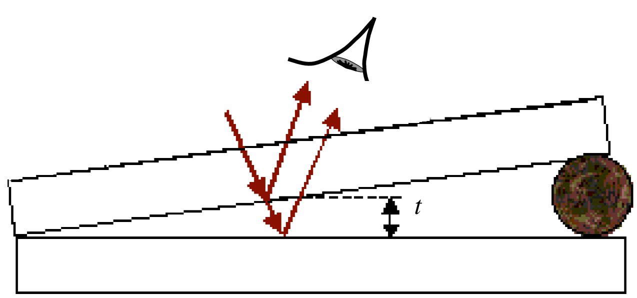


Figure 1- Air wedge formed by inserting a very thin object (e.g., a hair) between two glass plates

Whether the waves emerge in phase (bright fringe) or out of phase (dark fringe) depends on:

1. The additional distance traveled by the light that enters the wedge (path length difference)
2. Any phase shift upon reflection at either surface.

Since the light reflected at the upper surface is traveling in glass (n=1.5) and reflected by air (n=1) it does not undergo a phase change. The light reflected at the bottom surface is traveling in air and reflected by glass, so it does undergo a $\lambda/2$ phase change.

At the point where the two plates are in contact, the path length difference between the two rays is negligible (much less than the wavelength of the light) but there is still an air film at that point, although a very thin one. Since the rays go approximately the same distance (path length difference ≈ 0 compared to the wavelength of light) and since one ray is phase shifted by half a wavelength, we expect that the rays will emerge out of phase and there will be a dark fringe at the contact point.

Further to the right in Figure 1, when $t = \lambda/4$, the light that travels the extra distance will go an additional $2t = \lambda/2$. Because of the phase shift at the lower surface, the rays will emerge in phase and there will be a bright band. The next dark bands occur when $t = \lambda/2$, λ, $3\lambda/2$, and so on. That is, dark bands occur when

$$2t = m\lambda \qquad m = 1,2,3...$$

By counting the number of dark fringes (m), the thickness of the object forming the wedge (t) may be determined.

Procedure:

1. Clean the glass plates thoroughly with isopropyl alcohol and lens tissue. Allow to dry.
2. To make a monochromatic source of light, wrap a mirror with wax paper and illuminate it with the laser beam. (See Figure 2)
3. Cut a small square of plastic from a trash bag (or other paper or plastic of known thickness) and place it between the glass plates at one end to make an air wedge. You may need to adjust the plates by gently pressing on the top plate to produce straight fringes that cross the plate horizontally.
4. Place the air wedge under the light source so that it is evenly illuminated. Look at the plates from above the source to find the dark and bright interference fringes. If you don't see them at first, change your viewing angle slightly. The fringes appear to "float" between the plates. Placing the plates on a different colored background may also help.
5. Note whether the fringes are straight or curved. Sketch the general shape of the fringes that you see.

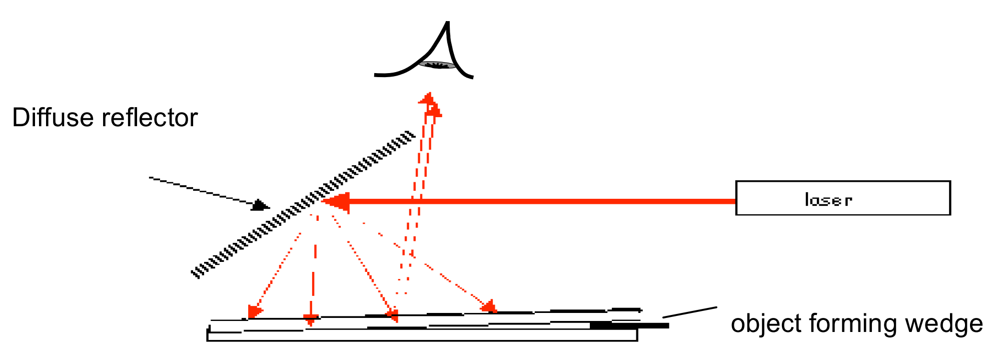


Figure 2 - Experimental set up. You may also expand the beam with a short focal length concave mirror

6. Determine the total number of dark fringes from the point of glass contact to the edge of the paper. (Hint: try counting the number of fringes per cm at several locations and multiplying by the total length.) A magnifying lens may help.
7. Replace the plastic with a hair, placed straight across between the ends of the glass slides. Again, count the number of dark fringes from the point of contact to the hair.

Analysis (calculations/observations) :

1. Determine the thickness of the plastic and compare to the known value by computing % error.
2. Determine the thickness of the hair.

Conclusions:

1. Note any particular difficulties you had in counting the fringes, and describe the procedure you used to overcome them.
2. What does the curvature of the fringes indicate? How can you minimize this curvature?
3. What happens to the fringes as the wedge angle increases? What does this imply for the thickness of plastic you can measure with this technique?

Applications/Explorations:

1. Applications of thin films are numerous in optics for example, thin film coatings are applied to lenses and other optics to reduce reflection ("AR", or antireflection coatings) and to make wavelength specific filters. The rainbow colors seen in a soap bubble or oil slick on water are thin film effects. Can you explain how the colors in a soap bubble form? What is the effect of the index of refraction of the soap film?
2. The fringes in this experiment are sometimes called "Newton's rings." Isaac Newton first observed similar fringes formed by the air film between a flat piece of glass and a lens. What would the fringes formed by a spherical surface on a flat glass plate look like? How could you tell if the spherical surface is concave or convex? What would irregularities in the spherical surface look like? Would this method be useful for testing the curvature of lens surfaces?

Air Wedge
Data/Results

Type of Light source ____________________________
Wavelength___________________

Trial #1: Wedge formed by object of known thickness (e.g., trash bag)

object used to make wedge	
known thickness of object	
length of wedge (point of contact to end)	
total number of fringes	
thickness of object, measured by air wedge	
% error	

Trial #2: Wedge formed by hair

length of wedge	
total number of fringes	
thickness of hair measured by air wedge	

Single Slit Diffraction

Safety Notes

Do not look into the laser cavity or at any reflections of the laser from shiny surfaces. Keep the beam at bench level so as not to accidentally shine the beam in the eyes of another person.

Objectives:

- To examine single slit diffraction patterns
- To determine the width of single slits from the diffraction pattern

Equipment:

- Diffraction slide with single slit(s)*
- Bar type lens holder or plate holder
  - (1) 3" post
  - (1) 3" post holder
- Laser and laser tilt table
  - (1) 2" post
  - (1) 2" post holder
- Meter stick and ruler

*If diffraction slide is unavailable, a single slit may be made by carefully scribing a thin line in heavy aluminum foil or a piece of aluminum beverage can. Carefully use a single edge razor blade and gentle pressure to create a slit approximately 1 cm in length.

Theoretical Background:

Light passing through a small slit bends at the edges, producing dark and light fringes on a distant screen. For a slit of width "s", the positions of the diffraction pattern minima (dark fringes) are given by

$$m\lambda = s \sin\theta \quad m=1,2,3...$$

That is, the diffraction angle θ for any order (m) depends on the ratio of wavelength to slit width (λ/s.)

In this experiment, the diffraction angle θ is very small, so the small angle approximation may be used:

$$\sin\theta \sim \tan\theta \sim \theta \text{ (the small angle approximation).}$$

Let x be the distance between the slit and the screen, and y the distance from the center of the diffraction pattern to the mth fringe. (See Figure 1.) Then

$$\sin\theta \sim \tan\theta = y/x$$

and we can write

$$m\lambda = s\,(y/x) \qquad m=1,2,3...$$

Unlike the double slit interference pattern, the single slit diffraction pattern does not have bright fringes centered between the dark fringes. The irradiance distribution of a single slit diffraction pattern is given by

$$E = E_o\left(\frac{\sin x}{x}\right)^2$$

Sin $(x)/x$ is called a "sinc" function, sinc(x), so single slit diffraction is sometimes to be represented by a "sinc squared"

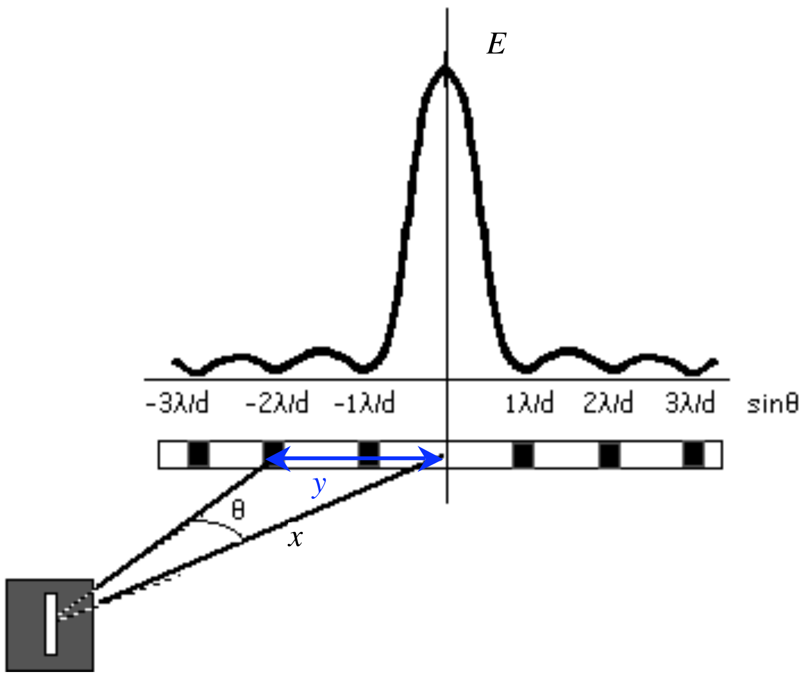


Figure 1 - The diffraction pattern formed by light passing through a single slit. In the figure, *y* is the distance from the center of the pattern to the m=2 dark fringe.

Procedure:

1. Place the diffraction slide at least two meters from a smooth wall. Tape a piece of white paper on the wall. Measure and record the distance from the slide to the wall.
2. Illuminate one of the single slit patterns with the laser and mark the positions of the centers of the dark fringes (minima) on the paper.
3. Remove the paper from the wall. Measure and record the distances between the first order minima, between the second order minima, and between the third order minima.
4. Repeat with a second slit.

Analysis (calculations/observations) :

1. Calculate the distance from the center of the pattern to each of the minima in the single slit pattern (one half the distance between the minima.)
2. Calculate the width (*s*) of each single slit for each measurement of single slit minima.
3. Compare calculated values to the known values by calculating percent error.

Conclusion:

Did your results verify the single beam diffraction equation? Why or why not? How does changing the width of the slit affect the diffraction pattern? How would changing the wavelength affect the diffraction pattern?

Applications/Explorations

1. Babinet's principle states that the diffraction pattern for an aperture in an opaque screen is essentially the same as that for an opaque obstruction of the same shape. For example, the rectangular slit and a rectangular piece of metal the same size would have the same diffraction pattern. This principle can be used to measure the width of a long thin obstruction (such as a hair). Use this method to measure the diameter of your hair by placing a hair over the end of a laser and analyzing the diffraction pattern seen on a distant wall. How could this principle be used to monitor and control the diameter of optical fiber as it is being drawn?
2. When you performed the double slit experiment, the interference was not equally bright across the pattern. The single slit pattern *modulates* the double slit pattern. What is the effect of the width of the slits on the double slit pattern? To minimize the effect of the single slit pattern (i.e., to make the double slit pattern have more uniform intensity across a wider portion of the center of the pattern) would you use wider or narrower slits?

Single Slit Diffraction
Data/Results

<u>Single Slit I</u>

laser wavelength__________

distance to screen__________

distance between 1st order min ________ y_1_______ *s*_____

distance between 2nd order min ________ y_2_______ *s*_____

distance between 3nd order min ________ y_3_______ *s*_____

average *s*_____

known slit width_____________

%error___________

<u>Single Slit II</u>

laser wavelength__________

distance to screen__________

distance between 1st order min ________ y_1_______ *s*_____

distance between 2nd order min ________ y_2_______ *s*_____

distance between 3nd order min ________ y_3_______ *s*_____

average *s*_____

known slit width_____________

%error___________

Malus' Law

Safety Notes

Do not look directly into the laser cavity, or at any reflections of the laser caused by shiny surfaces. Keep beam at bench level so as not to shine the beam accidentally into the eyes of another person.

Objective:

- To observe the operation of polarizers
- To verify Malus' Law

Equipment:

- Optical breadboard
- Rotary mount, removed from assembly and mounted vertically
- HeNe Laser (polarized output) with Tilt Mount
- Linear Polarizer
- Optical Power Meter
- (1) 2" Post
- (1) 2" post holder
- (1) 3" post
- (1) 3" post holder

Theoretical Overview:

Malus' Law is used to determine the power or irradiance of linearly polarized light after it passes through a linear polarizer. Malus' Law states:

$$E_2 = KE_1 \cos^2 \theta \qquad [1]$$

where $E1$ is the irradiance of the incident beam, E_2 is the irradiance of the beam transmitted through the polarizer, and θ is the angle of rotation of the polarizer axis relative to the polarization direction of the incident light. (Figure 1)

You may have seen Malus' law written without the factor "K." However, to obtain good results in the lab, we need to take into account that a real polarizer does not pass all the incident light even when the polarizer is aligned with the direction of polarization of the incident light (θ=0°.) In a real polarizer, some of the incident light is lost due to absorption and reflection in the polarizer. To account for these effects, a constant K is included in the equation. K is determined experimentally by measuring the irradiance before (E_1) and after (E_2) the polarizer when θ is set to 0°. That is,

$$K = \frac{E_2}{E_1} \text{ measured at } 0^\circ \qquad [2]$$

In this lab, you will determine K, and then verify Malus law by passing linear polarized light through a polarizer, varying the angle θ. If the room is not very dark, you will also need to correct the power meter readings for ambient light.

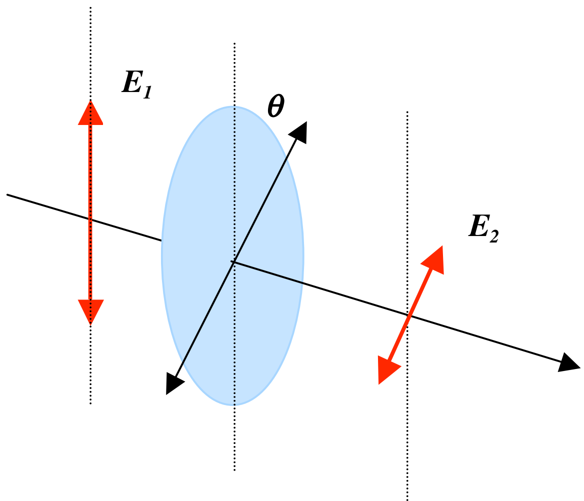
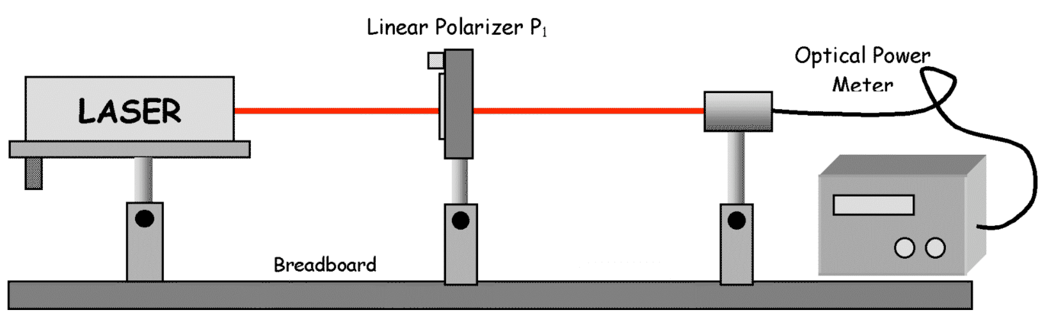


Figure 1 - Geometry for Malus' law experiment

Procedure:

1. To minimize power fluctuations, turn on the laser at least 15 minutes prior to taking data. Use an appropriate scale on the optical power meter. (Do not attempt to record excessive precision.)
2. Place the optical power meter in the path of the laser beam. Be sure the beam is centered on the detector, and the meter dial is set to an appropriate scale (2 mW for the Melles Griot SRP 810 and 812 lasers). Record the laser output power in the data table as $P1$. (Note: if a laser with polarized output is not available, a second polarizer, oriented with transmission axis vertical, may be used to produce the incident polarized light. P_1 would then be the power of the laser plus the additional polarizer,)
3. Set up the system shown in Figure 2. Note that the polarizer screws into the rotary mount. To align the rotary mount axis with the polarizer axis, set the mount so that it indicates 90° and rotate *polarizer* (holding the rotary mount stationary) until the meter reading is minimum. After this point, *do not* turn the polarizer; adjust only the rotary mount so that rotation angle



may be determined from the scale.

Figure 2 - Malus law experiment

4. To determine the ambient (background) light power, record the minimum power reading observed in step 3 as P_A in the data table. This reading will be subtracted to adjust all power

readings. If the room lights are off, P_A will probably be negligible and will not need to be subtracted.

5. Return the rotary mount to 0º. Record the power as $P_2(0°)$. Notice that $P2\ (0°) < P_1$. (Some of the incident light is absorbed or reflected by the polarizer.)
6. Now rotate the polarizer from 0 to 90° taking power readings every 10°. Record the values in the data table.

Analysis (calculations/observations) :

1. If necessary, calculate the corrected power by subtracting P_A from each of the power readings.
2. Calculate K from equation (2) and your values of P_1 and P_2, taken at 0º. Use the corrected values if the ambient light power is not negligible.
3. Calculate the (P_2/KP_1) for each angle measured. The values should range between 0 and 1. Use corrected values if the ambient light is not negligible.
4. Make a graph of $\cos^2\theta$ for angles from 0º to 90º. On the same graph, plot your measured values of the fraction of incident light transmitted (P_2/KP_1).

Conclusion:

Do your results verify Malus' Law? Why or why not? In your answer, explain why you can use the incident and transmitted power, P, rather than the incident and transmitted irradiance, E.

Applications/Explorations:

1. Suppose two polarizers are oriented so that their transmission axes are at 90º to each other. What happens if you put a third polarizer between the two crossed polarizers so that its transmission axis is 45º to the first? Explain what you see.

2. Materials that rotate the plane of polarization of light are called "optically active". Try putting some or all of the following between two polarizers whose transmission axes are crossed: corn syrup, a plastic protractor, a piece of mica or other crystal. Explain what you see. Where do the colors come from?

3. If you own a pair of polarizing sunglasses, look at the LCD screen of your calculator while wearing the glasses. Explain what you see. You may also notice the rear windows of some automobiles show patterns when viewed with your sunglasses. Can you explain why?

Malus' Law
Data/Results

P_A = ___________
P_1=_______________
P_1(corrected)* = ______________
$P_2(0^o)$ = ___________
P_2 (0^o, corrected)* = ______________

$K = P_1$(corrected)/ P_2 (0^o, corrected) _______________

θ	P_2	P_{2}(corrected)*	P_2/KP_1	$\cos^2\theta$
0				
10				
20				
30				
40				
50				
60				
70				
80				
90				

* If the ambient light is negligible, readings for P_1 and P_2 do not need to be corrected. If correction for ambient light is needed, the ratio P_2/KP_1 should be calculated with corrected values.

Brewster's Angle

Safety Notes

Do not look directly into the laser cavity, or at any reflections of the laser caused by shiny surfaces. Keep beam at bench level so as not to shine the beam accidentally into the eyes of another person.

Objectives:

- To measure and graph percent of light reflected versus incident angle for polarized light
- To measure Brewster's angle Equipment/Supplies (Items from the PHOTON lab kit)

Equipment/Supplies:

All components are to be mounted on an optical breadboard

- HeNe Laser on tilt table (laser with polarized output, or laser with linear polarizer to create polarized output)
- Rotational Mount, set up for rotation around a vertical axis
- Rectangle from acrylic shapes kit (or flat piece of glass) to reflect the laser beam
- Optical Power Meter
- (1) 2" post and (1) 2" post holder
- (1) 3" post and (1) 3" post holder

Theoretical overview:

When light strikes the surface of a dielectric (non-conducting) material, a portion of the incident light is reflected and the remainder is transmitted into the material. The fraction of the incident light that is reflected depends on both the angle of incidence and the polarization direction of the incident light. The functions that describe the reflection of light polarized parallel and perpendicular to the plane of incidence are called the Fresnel equations. (The plane of incidence is the plane that contains the incident and reflected rays and the normal to the surface.)

Figure 1 shows a graph of the Fresnel equations for components of polarization parallel and perpendicular to the plane of incidence. Note that the perpendicular ($\perp$) component of polarization is almost always reflected more strongly than the parallel (||) component. The exception occurs at normal incidence and at near 90° incidence, where both components are reflected equally. Figure 1 also shows that for one angle of incidence, called Brewster's angle, none of the parallel polarization is reflected.

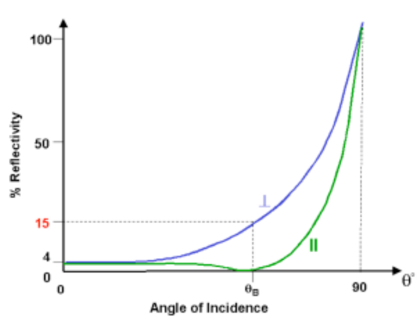


Figure 1 – Graph of the Fresnel equations showing the percent of incident light reflected for parallel and perpendicular polarizations

Because the electric field is a vector, natural (randomly polarized) light can be represented by components of polarization parallel and perpendicular to the plane of incidence. If natural light is incident on a dielectric surface, the Fresnel equations describe the percent reflection for each of the polarization components. Thus, natural light is always at least partially polarized upon reflection.

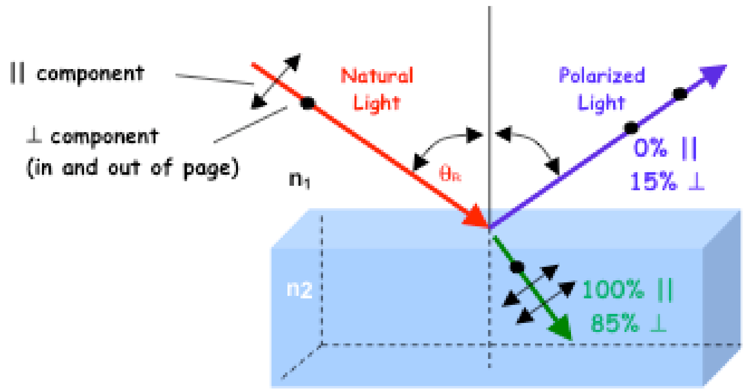


Figure 2 – Natural light striking a dielectric surface at Brewster's angle

At Brewster's angle, the reflected light is completely polarized perpendicular to the plane of incidence. The transmitted ray contains all of the parallel component and 85% of the perpendicular component. Brewster's angle (θ_B) depends on the indices of refraction of the incident medium (n_1) and the reflecting medium (n_2) and is given by

$$\tan\theta_B = \frac{n_2}{n_1}$$

In this experiment, you will reflect linearly polarized light from a plastic or glass surface and verify the graphs of the Fresnel equations. You will also determine Brewster's angle and the index of refraction of the reflecting material.

Procedure:

1. Set up the system shown in Figure 3. Be sure the glass or plastic reflecting material is vertical and centered over the axis of rotation of the rotational stage. Begin by having the laser beam strike the reflecting material at normal incidence, so that the reflected beam goes back into the laser aperture. Be sure the rotational stage reads 0º at this point.
2. Darken the room as much as possible. If there is measurable ambient light you will need to subtract the ambient light power from each measurement.
3. If the direction of polarization of the laser is not marked near the laser output aperture, use the linear polarizer to determine the polarization axis for the laser. Adjust the laser so the output is horizontally polarized. As shown in Figure 3, horizontal polarization is parallel (||) to the plane of incidence.
4. Record the power of the light incident on the reflector (the laser output power) as P_o. It is a good idea to check this measurement periodically to be sure there is no significant fluctuation in incident power
5. Starting at normal incidence, slowly rotate the glass or plastic piece from 0^0 (or as close as you can get to normal incidence) to close to 90º and measure and record the power of the reflected beam. ($P_{//}$) at 10º intervals. You will not be able to record the reflection at

0°, but measure the reflection at as small and incident angle as possible. Between the angles of 50° and 70°, measure the intensity of the reflected beam at smaller increments so that your graph will be smooth. You should notice that at a certain angle, Brewster's angle, there will be little or no reflected light. Be sure to take adequate data points at and around this angle.

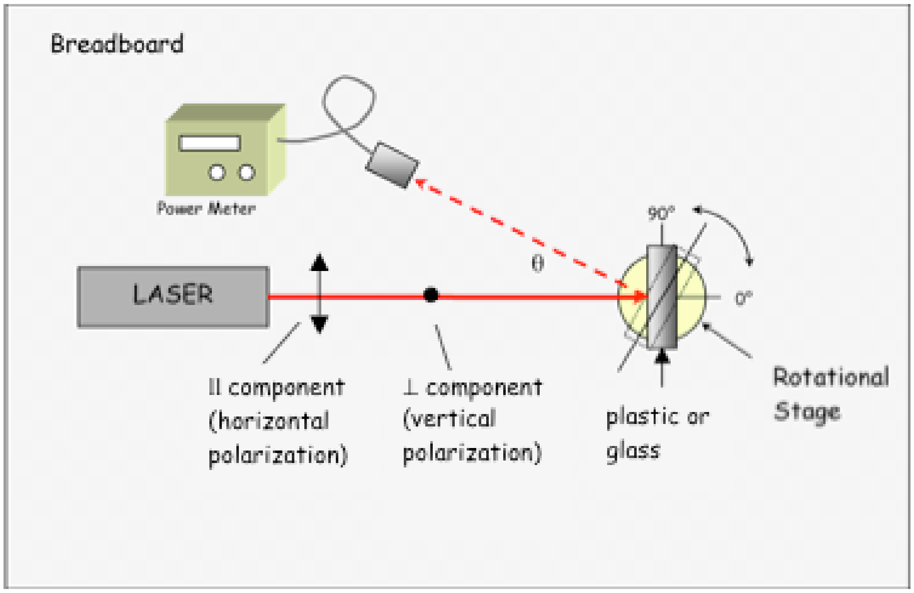


Figure 3 - Experimental set up

6. Rotate the laser so that the light is now vertically polarized. (Vertical polarization is perpendicular to the plane of incidence.)
7. Repeat steps 3 and 4, recording the power of the reflected beam as $P_\perp$. Does the reflected beam disappear at any angle for this polarization

Analysis (Calculations/Observations):

1. Calculate the percent reflected power for each polarization direction

$$\%R_\parallel = \frac{P_\parallel}{P_o} \quad \text{and} \quad \%R_\perp = \frac{P_\perp}{P_o}$$

2. Make a graph of percent reflected power versus θ for both polarization components. On the graph, note Brewster's angle (the angle where none of the parallel component is reflected
3. Using n=1 for air and Brewster's angle from your data, calculate the index of refraction for the reflecting material.

Conclusion:

How does your graph compare to the graph shown in Figure 2? From your graph, what is Brewster's angle? What is the index of refraction of the plastic or glass reflecting material? If you have measured the index of refraction in a previous lab, how does this measurement compare to the earlier measurement?

Applications/Explorations:

1. The application of polarization by reflection you are probably most familiar with is sunglasses designed to eliminate glare. Since the light reflected from a non-conducting surface, such as water or snow, is polarized parallel to the surface (perpendicular to the plane of incidence), sunglasses made out of linearly polarizing material (such as used in this experiment) can be used to block the glare. How should the transmission axis in the sunglasses be oriented to accomplish this? If you have polarizing sunglasses, note how the glare reduction from a water surface, such as a lake, varies as you change your viewing angle. Explain, using the results of this experiment.
2. Have you ever noticed how shiny a long hallway looks when you look along its length? Yet if you walk to the shiny end, you find it's no more polished than where you were standing originally. Explain this observation using the results of this experiment and the graphs of the Fresnel equations.
3. Explain how windows set at Brewster's angle can be used to polarize the output of a laser.

Brewster's Angle
Data/Results

Laser output power, P_o_______________

θ (degrees)	$P_{\parallel}$	$P_{\perp}$	% $P_{\parallel}$	% $P_{\perp}$
10				
20				
30				
40				
50				
52				
54				
56				
58				
60				
62				
64				
66				
68				
70				
80				
90				

Gaussian Beam Profile Measurement

Safety Notes

Do not look directly into the laser cavity, or at any reflections of the laser caused by shiny surfaces. Keep beam at bench level so as not to shine the beam accidentally into the eyes of another person.

Objectives

- The purpose of this lab is to measure the irradiance (power) profile of a Gaussian laser beam.

Equipment/Supplies

- HeNe Laser
- HeNe Laser Tilt Mount
- Optical Breadboard
- 2” Post Holder and Post
- 3” Post Holder and Post
- Linear Translation Stage
- Index card
- 8 mm Microscope Objective and Mount
- Laser Power Meter

Theoretical overview

The irradiance profile a laser operating in the TEM_{00} mode has a *Gaussian distribution*. What this means is that at a given distance "*r*" from the vertical axis, the irradiance “*E”* of the beam falls off exponentially. The irradiance of the beam as a function of the distance “*r*” from the center of the Gaussian distribution is completely described by the function

$$E(r) = E_o e^{-2\left(\frac{r^2}{\omega}\right)} \qquad [1]$$

In this equation, parameter ω is the distance from the center of the beam where the irradiance E has dropped to $1/e^2$, or 0.135, times E_0, the irradiance at the beam's center. This is referred to as the *beam radius* or *beam waist* (See Figure 1).

In order to measure the beam profile, you will need to have a probe that is much smaller than the beam diameter. Commercial beam profiling systems use the tiny pixels of a CCD camera to image the beam. Computer software then calculates important beam parameters such as waist or the point of greatest beam energy. In this lab you will use an optical power meter, with the detector masked to reduce its size. You will also expand the beam, so that the detector size is small relative to the beam size. Your task is to measure the beam waist, predict the Gaussian form of the beam profile, and determine if the beam does indeed have a Gaussian shape.

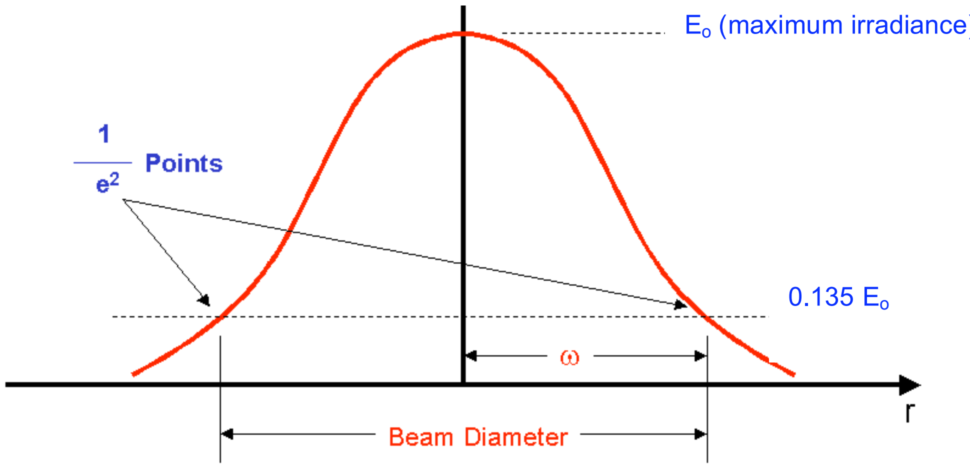


Figure 1. Gaussian Beam Profile

Procedure

1. Use opaque tape (such as black electrical tape) to block all but a 1 mm slit at the center of the detector head. (See Figure 2.)
2. Set up the optical system shown in Figure 2. Place the linear translation at a location where the expanded beam is about 2.5 cm in diameter at the location of the detector head. Record this distance (microscope objective to detector head.)

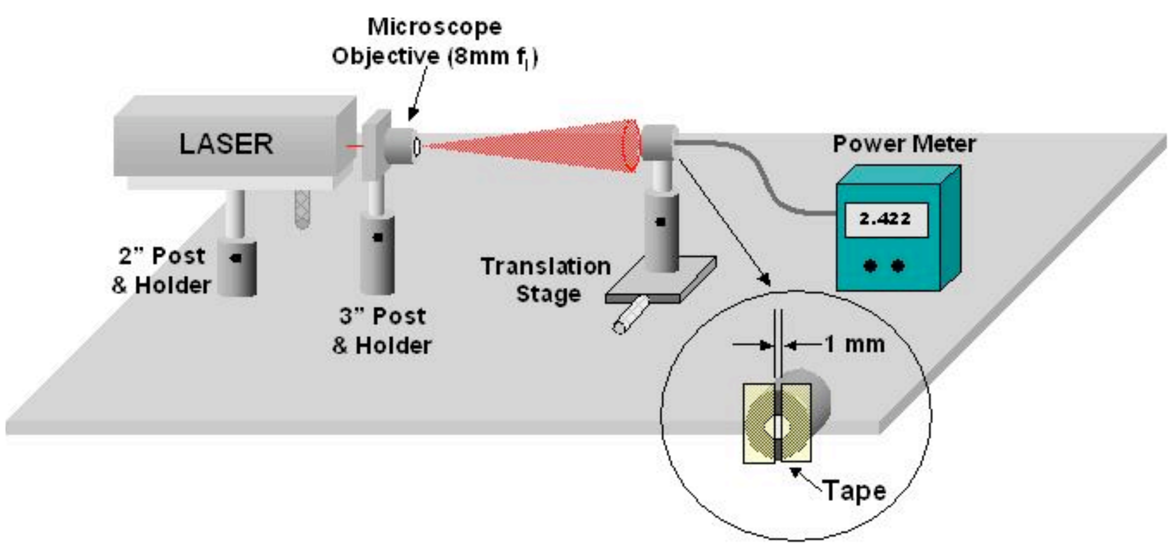


Figure 2. Gaussian Beam Profile Measurement Setup

3. Position the detector head in the center of the expanded beam so that it is uniformly illuminated.
4. Adjust the horizontal position of the detector head using the linear translation stage so that the power meter reads its maximum power. Record the maximum power P_0 and at this stage position, which corresponds to r=0.

5. Rotate the micrometer on the translation stage to move the detector head 1mm. Measure the power and the micrometer reading *r* at his point. Record *r* (1 mm) and *P(r)*.
6. Repeat step 4 until the power meter reads 0.135 times P_0. This value is ω, the radius of the Gaussian beam at this location. Record the value of ω in the data table. Continue to take a few readings at 1 mm increments beyond this point.
7. Move the detector head to a position where the expanded beam is approximately 5 cm in diameter. Record this distance (microscope objective to detector head.)
8. Repeat steps 2-6 making measurements in 2 mm increments.

Analysis/Calculations

For each of the two detector locations, use the value you found for ω and calculate the value of $P(r)$ using equation [1] with P_o replacing E_o for each value of r in the table. Graph the predicted Gaussian profiles as a smooth curves. Show your experimental data as points on the same graphs.

Conclusions

1. Did your experimental results confirm your theoretical results? Why or why not?
2. Does the intensity distribution of the expanded beam have a Gaussian form at both detector distances from the microscope objective? What does this tell you about relationship between distance and intensity distribution for a laser beam?
3. Equation [1] uses irradiance. Why can you use power instead of irradiance in the Gaussian equation?

Application/Exploration

The actual laser beam is much smaller than the expanded beams you measured. Use the result of this experiment to estimate the waist of the unexpanded beam.

Gaussian Beam Profile Measurement
Data/Results

2.5 cm Diameter Beam distance from objective to detector:_______ beam waist measurement:____________			5 cm Diameter Beam distance from objective to detector:________ beam waist measurement:____________		
Distance from *r*=0 (1 mm steps)	Predicted (Gaussian) Power P(r)	Experimental Power P(r)	Distance from *r*=0 (2 mm steps)	Predicted (Gaussian) Power P(r)	Experimental Power P(r)

The Principles of Bar Code Scanning

Safety Notes

Do not look directly into the laser cavity, or at any reflections of the laser caused by shiny surfaces. Keep beam at bench level so as not to accidentally shine the beam into the eyes of another person.

Objective:

- To illustrate the principles of bar code scanning.

Equipment/Supplies:

1. HeNe laser on tilt table
2. Light meter
3. (1) 2" post
4. (1) 2" post holder
5. "bar code" drawn with black stripes on white paper or photocopied on cardboard
6. opaque cardboard to form slit (see procedure)

Theoretical overview:

A bar code scanner consists of a laser, an optical detector, and a bar code. The bar code, also called a UPC (universal product code), is made up of contrasting black and white stripes or, in more advanced designs, a two-dimensional array of black and white blocks of varying size. As the laser scans the bar code, the beam is reflected by the white stripes and absorbed by the black stripes. The optical detector senses the presence or the absence of the beam and represents the signal electrically, usually in the form of a square wave. With the help of a computer, the bar code is matched to a specific item.

Procedure:

1. Mount the meter detector head into a short length [2 to 3 cm] of black cardboard or plastic tube to form a light shield. To improve the collection of light, you may want to mount a lens on the end of the tube.
2. Make a photocopy enlargement of a UPC code from a product. The widest black bars should be approximately 5 mm wide.
3. Cut a slit in a piece of cardboard that is the same size as one of the wide black bars in the UPC code you have enlarged. You will "scan" your code by drawing it past the slit.
4. Mount the laser so that the beam reflects off the UPC code and onto the detector. Pull the UPC code past the slit and notice the variations in received light intensity.

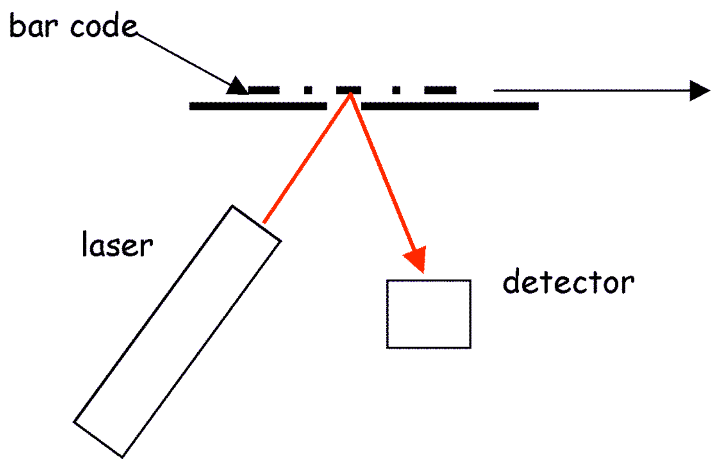


Figure 1 - Bar code scanner principle

Observations/Conclusions:

1. If you drag the test UPC code past the hole what do you see on the meter? State the maximum and minimum values observed.
2. What is the optical principal at work here?
3. What improvements can you make to this project to reduce interference from room light?
4. Bar code scanners that are placed in contact with the UPC code use LEDs but those that scan from a distance use lasers. What reasons can you give for this?

Applications/Explorations:

1. How can you automate your bar code scanner? Can you move the bar code continuously and capture the variation in reflected power on an oscilloscope? How does an actual bar code scanner move the beam across the bar code?
2. The elements of a bar code are the vertical lines of varying width and the spaces between them. Bar codes may contain numbers, letters and/or special symbols. Many different codes exist and are used by different industries (e.g., food, blood banks, postal service). For more information on bar codes and bar code scanners, visit: http://www.barcodehq.com/primer.html. At this web site, you will find the codes used in "code 39" to represent the letters A through E. How many words can you spell out in bar code using these letters?

Laser Range Finder

Safety Notes

Do not look directly into the laser cavity, or at any reflections of the laser caused by shiny surfaces. Keep beam at bench level so as not to accidentally shine the beam into the eyes of another person.

Objectives:

- To build a laser rangefinder to measure distances using trigonometry
- To examine the range of distances over which the range finder is accurate

Equipment/Supplies:

All components should be mounted on an optical table except the target, which should be movable to at least one meter from the beam splitter

- HeNe laser mounted on a tilt table
- 50/50 beam splitter, mounted on a base plate (used as a table)
- Mounted front surface mirror on rotational stage, mounted horizontally
- Post or similar pole to serve as target
- Posts and post holders as needed
- Meter stick

Theoretical overview:

A range finder is a device that allows you to find the distance from your position to an object without using a measuring tape. The range finder in Figure 1 uses right angle trigonometry to solve for the distance from the laser to the target (labeled "*x*"). If *L* is the length of reference beam, the length of the test beam, *x*, is given by

$$x = L\tan\theta$$

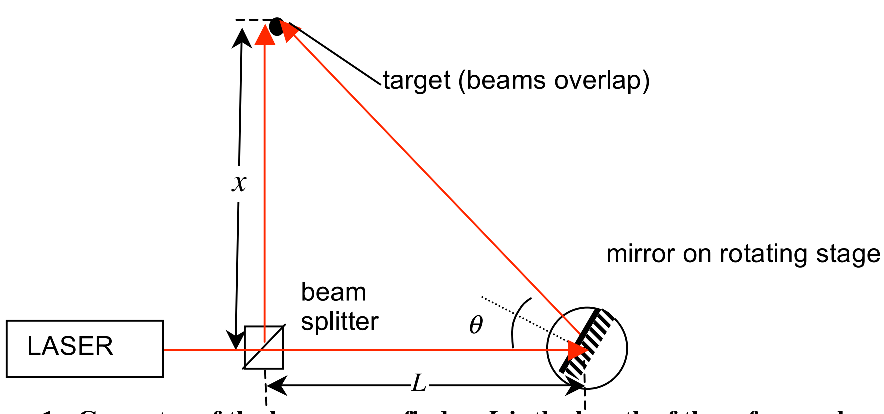


Figure 1 - Geometry of the laser range finder. *L* is the length of the reference beam.

Procedure:

1. Align the laser beam so that it is straight and level (maintains same height over board while traveling straight along a row of holes.)
2. Mount a 50/50 beam splitter on a base plate and place in front of the laser to split the beam into two beams. The angle between the test and reference must be exactly 90 degrees. (How can you ensure the beam splitter is exactly normal to the beam?)

3. Place the mounted first surface mirror on the rotating stage. Be sure the mirror is mounted directly over the center of rotation of the stage. You may use a piece of double stick tape to keep the mirror from shifting position.
4. Place the rotational stage and mirror about 50 cm from the beam splitter
5. Rotate the stage and mirror so that the beam returns directly to the laser. Note the angle of rotation of the stage. This is the zero position.
6. Place the target object approximately 1 meter from the range finder in the test beam path and adjust the object so that the test beam laser spot is clearly visible. Now rotate the mirror on the rotation stage so that the reference beam meets the test beam exactly. Note how many degrees the stage has rotated from the position in step 3. Record this as the "rotation stage angle, a" on the data sheet. The angle that the beam has rotated (θ in Figure 1) is *twice* the rotation angle of the stage. Record the beam rotation angle as θ in on the data sheet.
7. Use a meter stick to measure the actual target distance.
8. Repeat for a total of ten "unknown" distances including both close (10 cm) and distant (length of the room). Be sure to record the actual target distance each time.

Analysis (calculations/observations) :

1. For each of the target positions, calculate the target distance using right angle trig.
2. Plot a graph of range finder distance (calculated from angular displacement) vs. actual distance. On the same graph, draw a line for comparison representing a "perfect" rangefinder that always measures the actual distance correctly.

Conclusions:

What do you think limits the accuracy of the range finder (for near and distant objects)? Does your graph give an indication of the range over which the range finder is the most accurate? What would be the maximum and minimum distances that the range finder would be accurate? Compare your results with other students who used smaller or larger baseline distances "*L*."

Applications/Extensions:

The procedure states that the angle the beam rotates is twice the angle the mirror rotates (as measured by the rotation stage). Show that the beam rotation angle (θ) is twice the mirror rotation angle (α). (See Figure 2.)

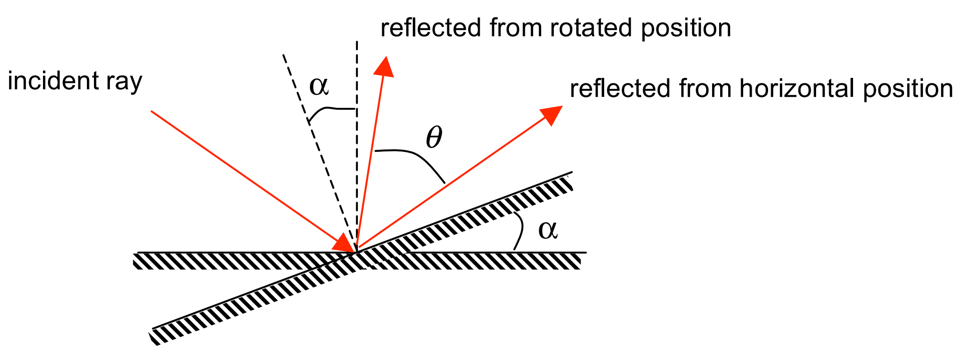


Figure 2 - Rotation of mirror and reflected ray

This effect is called an "optical lever" and can be used to magnify small motions. As a simple application, create a laser light show. Glue a small, lightweight mirror to the paper cone of an audio speaker and bounce a beam of laser light off the mirror while the speaker is playing. (*Be very careful to aim the reflected beam toward a wall and away from viewers!*) Experiment with different methods of mounting the mirror and with different types of music to get the best effect.

Or, use an optical lever to see your pulse! Place your arm flat on a table, palm facing upward. Place a very small mirror over the pulse in your wrist. (Lightweight plastic mirrors works best.) Have a friend shine a low power laser on the mirror, and watch the movement of the reflected beam on the wall or ceiling. *Be very careful to aim the beam away from viewers!*

Laser Range Finder
Data/Results

Length of reference beam________________

Measured Distance (x)	rotation stage angle, $\alpha = \theta/2$	beam rotation angle, θ	Calculated distance (x)

Numerical Aperture of an Optical Fiber

Safety Notes

Do not look directly into the laser cavity, or at any reflections of the laser caused by shiny surfaces. Keep beam at bench level so as not to shine the beam accidentally into the eyes of another person. Align the focused beam from the microscope objective to the fiber end with the room lights on.

Objectives:

- To demonstrate how light is coupled into a plastic multimode fiber
- To determine the numerical aperture of a plastic multimode fiber by different methods

Equipment/Supplies:

- piece of plastic optical fiber, at least one meter long
- HeNe laser mounted on tilt table
- (4) 2 " post
- (2) 2" post holder
- microscope objective, mounted in an objective holder
- (3) 3" posts and 3" post holders
- (2) base plates
- slide holder
- rotational stage
- power meter
- single edge razor blade
- alcohol wipe (or isopropyl alcohol and a lint free wipe)
- 600 grit emery paper
- black electrical tape
- meter stick or ruler

Theoretical overview:

The numerical aperture of a fiber is a measure of its light-gathering ability. The numerical aperture (*N.A.)* is defined as

$$N.A. = \text{Sin}\ (\theta_a)$$

where θ_a is the half-acceptance angle of the fiber. (See Figure 1.) The acceptance angle defines the cone of rays that will be "accepted" and propagated by the fiber. Rays entering the fiber at angles larger than the acceptance angle will be refracted into the cladding and not guided along the core. As θ_a increases from 0° to 90°, sin (θ_a) increases from 0 to 1. That is, the numerical aperture varies from 0 to 1.

Like the critical angle, the numerical aperture is dependent on the index of refraction of the core material, (n_1) and the index of refraction of the cladding (n_2). If these two values are known, then *N.A.* is calculated by

$$N.A. = \sin\theta_a = \sqrt{n_1^2 - n_2^2}$$

Numerical aperture is used to determine the coupling and dispersion characteristics of a fiber. A large numerical aperture typically allows for more efficient coupling and ease of handling, termination, and splicing, but at the expense of modal distortion, which causes pulse spreading leading to bandwidth limitations. A fiber with a smaller numerical aperture is more difficult to work, but does not suffer from modal distortion, which allows for higher bandwidth communications.

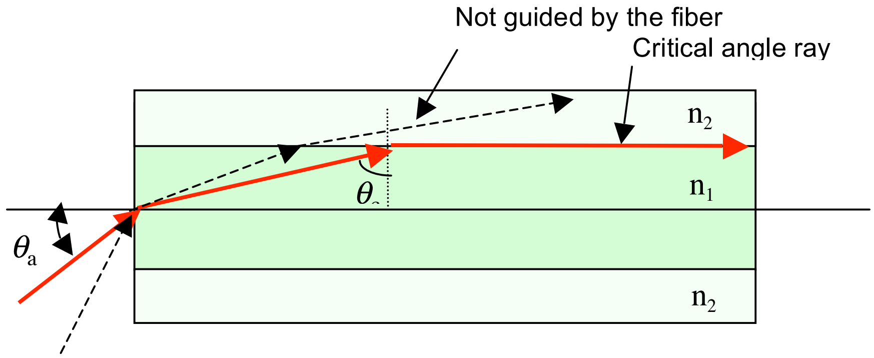


Figure 1- θ_a is the half acceptance angle and θ_c is the critical angle

Many methods are used by the fiber optic industry to measure the *N.A.* of a fiber. You will use modifications of two of these methods to measure the numerical aperture of a plastic optical fiber. Both methods rely on the cone of light leaving the far end of the fiber having the same angle as the cone of light accepted by the fiber (defined by the acceptance angle.)

In the first method, the fiber is set about 20 cm-30 cm from a small area detector. The illuminated fiber is rotated so that the exiting cone of light sweeps across the detector, and the power is recorded as a function of angle. The angle at which received power drops to 5% of maximum is noted, and the sine of that angle is the *N.A.* The received power is plotted as a function of rotation angle of the fiber. Figure 2 is a schematic diagram of the first method.

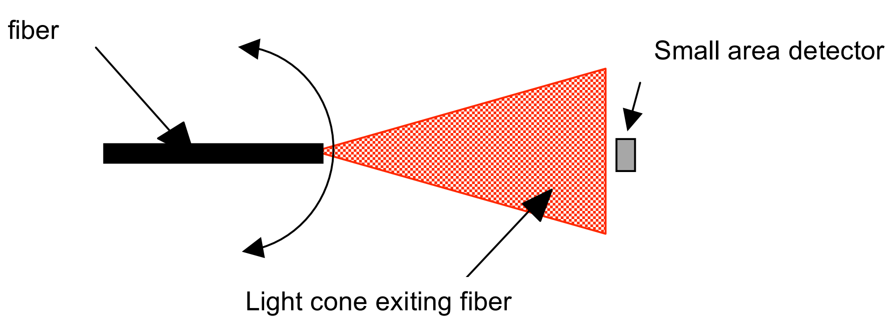


Figure 2 - Measuring the *N.A.* with a detector

The second method is more direct. The cone of light leaving the fiber is observed on a sheet of paper and the acceptance angle is measured directly. Both methods require that the ends of the fiber be flat and clean.

Procedure:

Fiber end preparation

1. Lay the 1-meter length of 940/1000 multimode plastic fiber on a hard flat surface (e.g., lab bench) and "cleave" off approximately 1/4 inch from both ends of the fiber using the razor blade. Try to make as smooth and square a cut as possible.
2. Place the 600 grit paper on the hard flat surface (make sure the surface is clean and free of debris first).
3. Polish each end of the fiber by making approximately 10 "figure 8's" on the polishing paper with each end of the fiber as shown in Figure 3. Apply gentle pressure and hold the fiber vertical so the end remains square. Wipe the fiber ends with an alcohol wipe.

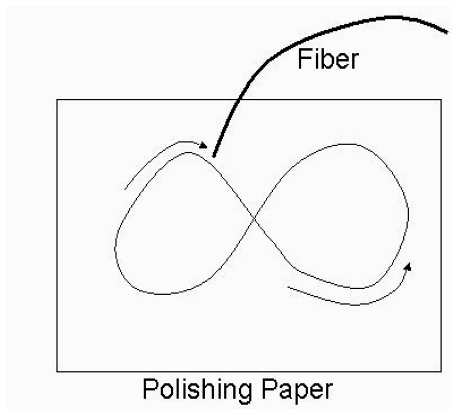


Figure 3 - Polishing the ends of the fiber

Numerical Aperture Measurement by Power Curve Method

1. Mount the laser on the tilt platform assembly on the optical breadboard using the 2-inch post and post holder. Make sure the 1/4-20 mounting screws are all tight.
2. Using a ruler, check that the laser beam is level and straight.
3. Mount the microscope objective assembly on the optical breadboard approximately 1 inch from the laser. Use a 3 inch post and post holder and place the post holder on a base plate to allow for side-to-side adjustments.
4. Mount the slide holder on a 3 inch post and post holder, again using a base plate. Place one end of the fiber into the slide holder and clamp gently. Adjust the position of the slide holder assembly so that the microscope objective focuses the beam on the end of the fiber. Tighten all mounting screws.
5. The other end of the fiber must be mounted securely over the center of rotation of the rotary stage. Mount the rotational stage on a 2 inch post and post holder, and tape the fiber to stage so that the end of the fiber is over the center hole. The stage should rotate without disturbing the fiber position.
6. Using black electrical tape, mask off all but a 2-4 mm slit on the optical power meter detector opening. Place the detector about 30 cm from the fiber end.
7. Turn off the room lights for the remaining steps. To set the zero point for power measurements, make sure angle dial is set for 0 degrees on the rotational stage assembly. Loosen the post holder screw on the rotational stage and adjust the stage vertical

positioning for maximum power as indicated by the power meter. Adjust horizontal positioning for maximum power as indicated by the power meter. When maximum power has been achieved securely tighten the mounting screws.

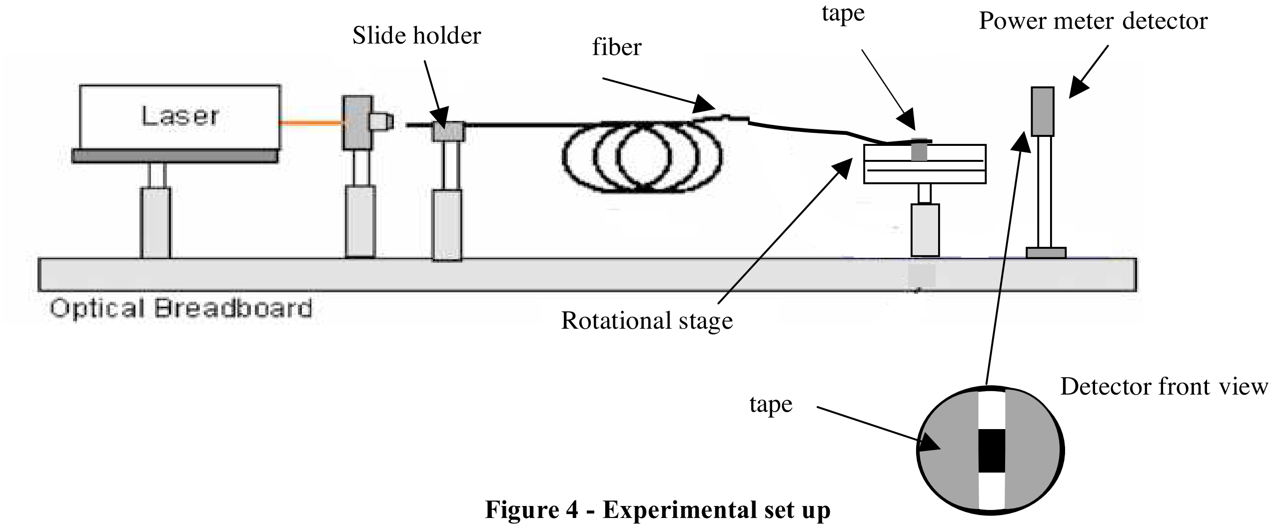


Figure 4 - Experimental set up

8. Read and record the output power at 10° increments as the rotational stage is turned from about –40° to +40°. Be sure the fiber does not slip as the stage is turned. (Optional: repeat measurements twice more and average for increased accuracy.)

Analysis/Calculations- Power Curve Method:

Plot a graph of received power versus angle. Draw a smooth curve through the data. On the graph, note the points where the power falls to 5% of maximum on either side of the center point. Calculate the half acceptance angle and the numerical aperture.

Direct measurement method

1. Tape a sheet of 8 1/2 x 11" paper onto the optical breadboard. Turn off the laser.
2. Remove the end of the fiber from the rotating mount and tape it onto the sheet of paper as shown in Figure 5.

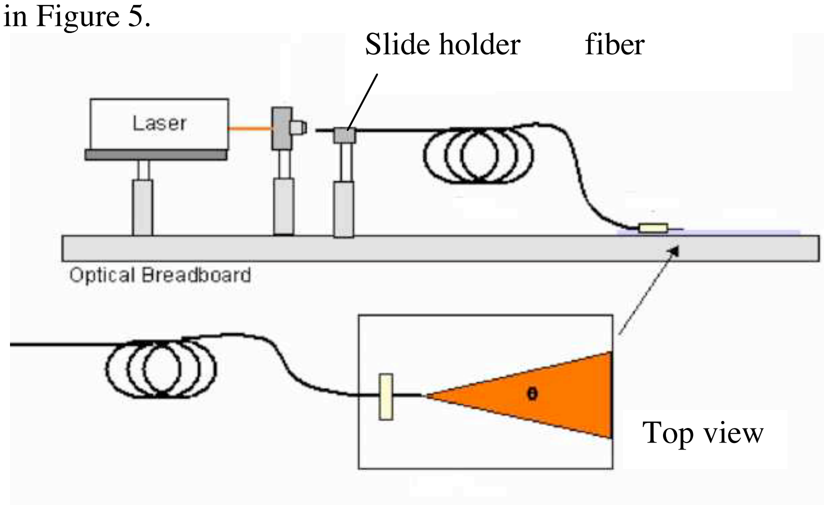


Figure 5 - Direct measurement method

3. Turn the laser back on and be sure the beam is focused on the end of the fiber near the microscope objective. Trace the light pattern onto the paper using a pencil and ruler.
4. Turn off the laser.
5. With a protractor, measure full acceptance angle of the fiber.

Analysis/Calculations- Direct Measurement Method:

Calculate the half acceptance angle and the numerical aperture.

Conclusions:

Compare the results obtained by the two different methods. What are the good and bad features of each type of measurement? Which do you think gave more accurate results? Why?

Applications/Explorations: Observation of Modal Patterns

You can see the individual modes by allowing the light leaving the fiber to shine onto a clean piece of white paper. Using the microscope objective to couple light into the fiber, as in Figures 4 and 5, hold the fiber so the light leaving the end of the fiber shines onto a piece of paper taped to a wall. The output of the multimode fiber should look like Figure 6. Gently shake the fiber and observe the modal pattern. It should vibrate. This is known as *mode conversion.* By changing the shape of the fiber, the paths through which the modes travel change, affecting the output. This only occurs in multimode fiber. What happens if you bend the fiber into a tight curve?

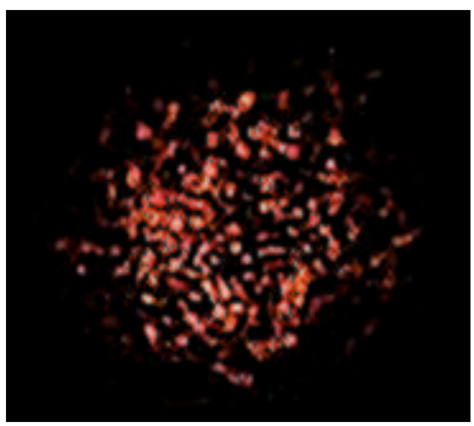


Figure 6- Fiber Modes

Numerical Aperture of an Optical Fiber
Data

Power Curve Method

Angle	Power	Power (optional data set)	Power (optional data set)

Direct measurement method

Full acceptance angle________________________

Fiber Optic Distance Measuring Sensor

Safety Notes

Do not look directly into the laser cavity, or at any reflections of the laser caused by shiny surfaces. Keep beam at bench level so as not to shine the beam accidentally into the eyes of another person. Align the focused beam from the microscope objective to the fiber end with the room lights on.

Objectives:

- To construct a fiber optic sensor that can be used to measure distance
- To determine the useful range of the sensor
- To calibrate the sensor and use the calibration to predict future cases

Equipment /Supplies:

- Plastic optical fiber
- Small stick (like a coffee stirrer) and tape
- Fiber prep materials: single edge blade or scissors, 600 emery paper, isopropyl alcohol and wipe or pre-packaged alcohol wipe, electrical tape)
- Laser and tilt-table mount
- Microscope objective in holder
- Optical power meter
- Clamps and mounts as needed (the slide holder can be used for the source end of the fiber)
- Translation stage

Theoretical overview:

Light exiting from the end of an optical fiber forms a "light cone" with a central angle equal to twice the fiber acceptance angle. The same is true for light entering the fiber; only light entering within the acceptance cone will propagate down the fiber.

If two fibers are placed side by side, the light emitted from one fiber may be reflected off of a surface and reflected into the other fiber. The actual power received will depend in a complicated fashion on distance from the reflector, since it involves the intersection of two cones of light with the surface. (See Figure 1.)

In this lab you will construct a sensor to detect and measure distance from a surface. The sensor will be placed near a reflective surface and moved in small increments. (Note: the sensor may also be held stationary, and the reflective surface moved instead.) At each step, you will measure the reflected light power received from the sensor receive fiber. (See Figure 2.) You will need to determine the useful distance range for your sensor and then calibrate the sensor for use over this range.

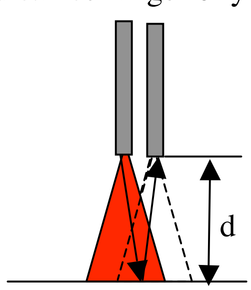


Figure 1 – Sensor geometry

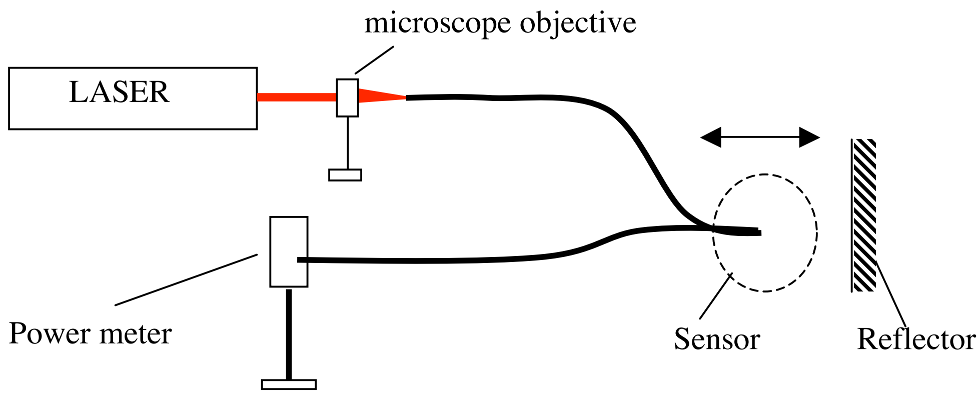


Figure 2 – Schematic of sensor with laser and meter. Either the sensor or the reflector may be moved. The sensor may be held horizontal or vertical, as you prefer.

Procedure (This is a suggested procedure. Feel free modify to suit your own equipment and supplies.)

1. You will need two pieces of fiber, each about 25-30 cm long. You can cut the fiber with a single edge razor blade, or (if nothing else is available) with scissors. The best end finish results from using a hot melt knife.
2. Polish and clean the ends of the fiber. (This step is not necessary if you used a hot melt knife.) Hold the fiber vertical with the end on the emery paper and make a few figure eights to polish the end. Wipe the fiber end clean with isopropyl alcohol. Repeat for each end.
3. Carefully tape the two fibers together at one end side by side, keeping the ends even. A small stick or coffee stirrer between the ends helps hold the sensor rigid.
4. Mount the input fiber end horizontally in the slide holder (or other clamp) and position the laser and microscope objective so that the beam is focused on the fiber end. Mount the other fiber end (the receive fiber) so that light leaving the fiber will enter the optical power meter.
5. Mount the sensor on the translation stage and secure with tape. Be sure the sensor is mounted along the direction of movement of the stage.
6. Place the translation stage so fiber sensor close to a reflective surface. Secure the stage to the table. You can use a small mirror, or a shiny table surface. You will need to move the sensor away from the surface in small increments, so you will need a way to both move the sensor and to measure the distance from the surface. (Note that you can also move the reflective surface and keep the sensor stationary, if that is more convenient.)
7. Beginning with the fibers very close to the surface, measure and record the distance from the end of the sensor to the surface and the received optical power. Since the power will be quite small, you will need to turn off the room lights or cover the detector.
8. Move the sensor a few millimeters (up to one centimeter) and measure and record distance and received power. Continue to move the sensor until there is no longer any change in received power. You should have 8-10 measurements from the smallest to largest distances. Go back and take additional measurements as necessary.

Analysis (calculations/observations) :

1. Make a graph of reflected power versus distance.

2. What are the limitations of this sensor? (Consider both very small and very large distances.)
3. Find the range over which the sensor is approximately linear. Determine the equation of the straight line for this portion of the graph. (That is, find the slope and intercept.)
4. How could you use the meter readings to determine how far the sensor is from a reflective surface?

Applications/Explorations:

Any physical change to a fiber that changes the light passing though the fiber can be incorporated into a sensor. For example. the end of a fiber may be coated with a substance that, in the presence of a certain chemical, changes the amount or wavelength of light that reflected. Such sensors can be used to monitor chemicals in potentially hazardous environments. What other types of sensors can you construct with the plastic fiber in the PHOTON2 kit?

Fiber Optic Distance Measuring Sensor

Data

Distance	Received Power

Single Beam Reflection Hologram

Safety Notes

Do not look directly into the laser cavity, or at any reflections of the laser caused by shiny surfaces. Keep beam at bench level so as not to shine the beam accidentally into the eyes of another person.

Preliminary notes:

Have all developing chemicals mixed and arranged in the order that they will be used before beginning. Be sure to follow directions on the packages.
Check the alignment of the optical system before exposure—then check it again.
The safelight for red sensitive holography film is green. A green nightlight, placed away from the film developing process, will work well.
During exposure, the entire optical set up must remain vibration free. Do not move around or touch the table during exposure.
Be sure to dispose of spent chemicals safely, following all state and local regulations.

Objective:

- To create and view a single beam reflection hologram

Equipment/Supplies:

- developing chemicals, mixed per instructions on the package
- trays for developing chemicals
- source of running water (or large pail of tap water)
- holography film plates
- breadboard with three capscrews to mount film plate
- laser, mounted on tilt table on optical breadboard
- short focal length concave mirror mounted on breadboard
- object (1.5-2” tall, light colors work well. Small toys or models are ok)
- opaque cardboard for shutter

Theoretical Background:

A photograph is produced when light scattered from an object exposes a piece of light sensitive film. A hologram required the addition of a second beam of light, a reference beam that interferes with the light from the object (the object beam) to form a pattern of interference fringes. To view the hologram, light is either transmitted through or reflected from the interference pattern, depending on the geometry of the hologram construction. Diffraction of light by the pattern produces an exact replica of the light that originally left the object, preserving both amplitude and phase information.

To make a single beam reflection hologram, the same beam serves as reference and object beam (see Figure 1). The reference beam passes through the film on one side, strikes the object, and reflects as the object beam from the other side. The interference fringes are formed in the volume of the emulsion. In Figure 1, light is spread by a lens; however, you will use a concave mirror, which has the same effect but is simpler to align.

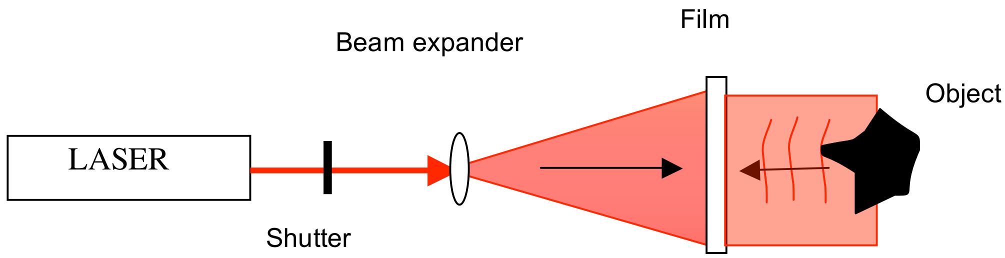


Figure 1 - Schematic of single beam hologram construction. The reference beam passes through the film and reflects off the object. The tow beams combine and interfere in the film emulsion.

After exposing the film, it is developed by similar techniques to developing black and white film, except that no print is made- the hologram is actually a film negative. The steps are outlined on the developer package insert.

To view the single beam reflection hologram, white light is reflected from the hologram surface, which, remember, is more similar to a diffraction grating than to a mirror. The reflected light forms a virtual image seen behind the film. (See Figure 2)

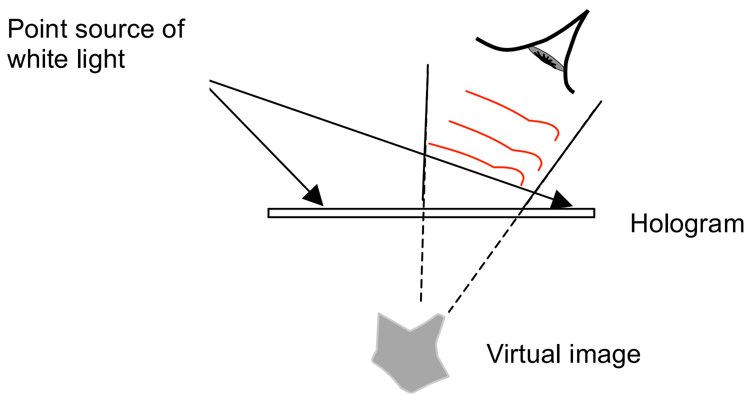


Figure 2 - Viewing a single beam reflection hologram. White light reflected from the developed emulsion forms and image behind the film plate. The color of the image depends on the type of film and how it was processed.

Procedure:

NOTE: This procedure assumes the use of PFG-03M film plates and JD-4 developer, available from Integraf (http://www.holokits.com/). If you use different film or developer, consult the manufacturer's instructions.

Setup:

1. Pour enough developer (equal parts A and B) into one developing tray to cover a film plate (around 1 cm deep). Pour a similar amount of bleach into a second tray. Fill a third tray with water only and add a few drops of Photoflo. Have a source of running water nearby. (If no running water is available, a large bucket of clean tap water will do.)
2. Arrange the counter so the film plates and developing trays are readily accessible. Clear away any other objects. Remember, you will be developing the film in the dark!
3. Set up the laser, mirror and object as shown in Figure 3. The concave mirror may be placed in a bar-type lens mount, then angled downward to direct the light onto the film plate and object below. To minimize vibrations, use a study table or bench and place the breadboard on shock absorbing material such as packing foam, a partially inflated inner tube, or sorbothane balls.

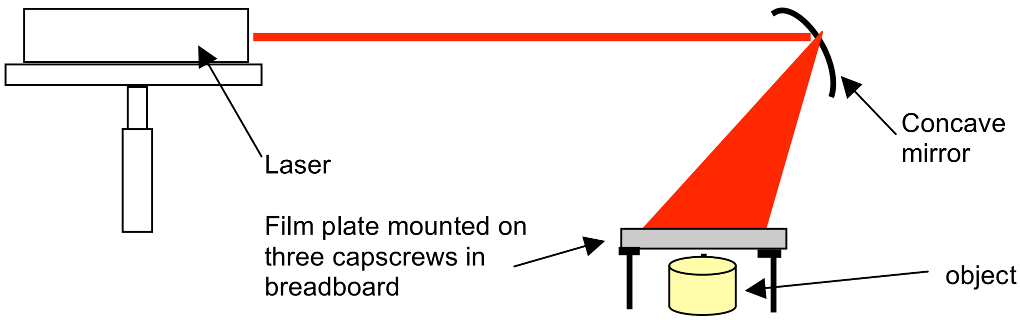


Figure 3 - Set up for film exposure

4. Be sure the cleanest and brightest portion of the beam is completely illuminating the object. The object should be close to the film plate. To aid in alignment, use an exposed film plate or piece of glass of the same size as the film plate.
5. Place a cardboard "shutter" in front of the laser.

Exposure:

1. Turn off the room lights. Remove one film plate from the box. Close the film box completely. Determine which is the emulsion side of the film plate (it is sticky when touched with a moistened finger).
2. Place the film plate emulsion side down (toward the object) on the three support screws, directly over the object.
3. Wait a minute or two (don't touch the table) before exposure to allow the emulsion to settle. Lift the shutter part way, so that the laser light is still blocked, and wait another minute for the vibrations to die out. Lift completely to expose the plate for about 8 seconds. (The actual time will depend on a number of factors, and is best determined through experience!)

Development:

1. Develop until about 80% opaque, or about as dark as dark sunglasses. If you have neutral density filters, you can develop until the film is about 2.0-2.5 OD.
2. Rinse about 30 seconds in running water.
3. Bleach until clear. (You may turn on the room lights after bleaching).
4. Rinse one minute in running water.
5. Soak 2 minutes in the Photoflo solution and air dry. The hologram will not be visible until it is fully dry. If you absolutely can't wait, dry gently with a hand held hair dryer.

Viewing:

Use a point source of light (a light bulb works well) and view the reflected light from the front of the glass plate to see the holographic image. The contrast is improved if you spray paint the back (emulsion side) surface with a flat black paint. You may need to tilt the plate and try different angles to see the image.

Conclusion:

Describe the difference between your hologram and a photograph of the object. Did your hologram have any distortions, especially as you turned it slightly while viewing it? What color does your hologram appear? What do you think causes the color of the hologram? (Remember, you used black and white film.)

Two Beam Transmission Hologram

(This experiment requires additional items not found in the basic PHOTON2 kit.)

Safety Notes

Do not look directly into the laser cavity, or at any reflections of the laser caused by shiny surfaces. Keep beam at bench level so as not to shine the beam accidentally into the eyes of another person.

Preliminary notes:

Have all chemicals mixed and arranged in the order that they will be used before beginning. Check the alignment of the optical system before exposure- then check it again.
The safelight for red sensitive holography film is green. A green nightlight, placed away from the film developing process, will work well.
During exposure, the entire optical set up must remain vibration free. Do not move around or touch the table during exposure.
Do not attempt this experiment unless you have a very stable table or bench to work on.

Objective:

- To create and view a two beam transmission hologram

Equipment/Supplies :

All components are to be mounted on an optical breadboard. The breadboard should be on a heavy bench or table, with additional vibration damping material between the table and breadboard (for example, neoprene mats or balls or foam packing material)

- developing chemicals, mixed per instructions on the package and trays for developing chemicals
- source of running water (or large pail of tap water)
- holography film plates or film, tightly sandwiched between glass plates
- plate holder for film
- laser, tightly secured to tilt table
- (2) microscope objectives in holders
- beam splitter on horizontal mount (rotational stage or base plate)
- Two mounted plane mirrors
- sturdy stand for object
- object (1.5-2" tall, light colors. Small toys ("mini figures" or models work well)
- opaque cardboard for shutter

Theoretical Background:

A photograph is produced when light scattered from an object exposes a piece of light sensitive film. A hologram requires the addition of a second beam of light, a reference beam that interferes with the light from the object (the object beam) to form a pattern of interference fringes. To view the hologram, light is either transmitted through or reflected from the interference pattern. Diffraction of light by the pattern produces an exact replica of the light that originally left the object, preserving both amplitude and phase information.

To make a two-beam transmission hologram, the beam from a laser is split into a reference beam and an object beam by a beam splitter. Each beam is expanded, usually with a spatial filter (a device that uses a short focal length lens to expand the beam and a small pinhole to remove optical noise.) In this lab you will use microscope objectives to expand the beams.

One beam is directed toward the object, where it reflects off the object and scatters toward the film. The second beam strikes the film directly. (See Figure 1) The object and reference beam are combined and interfere on the film plate. It is important that the two paths be equal within the coherence length of the laser.

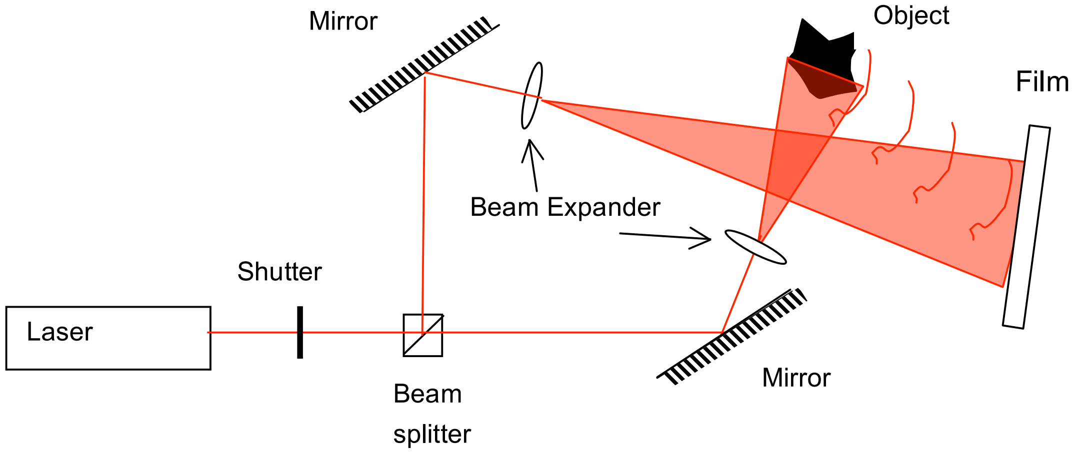


Figure 1 - Schematic of two-beam hologram construction. The object and reference beams interfere on the film plate. The two beams must travel approximately the same distance from beam splitter to film

After the film is exposed, it is developed by techniques similar to developing black and white film, except that no print is made- the hologram is actually a film negative. The steps are outlined on the developer package insert.

To view the hologram, the developed film is illuminated by a replica of the reference beam. Looking through the plate, the virtual image appears behind the film plate in the position of the original object. (See Figure 2.) One method to ensure the plate is illuminated at the correct angle is to replace it in the original reference beam, blocking the object beam with an opaque beam block. Look back into the film plate, toward the original position of the object.

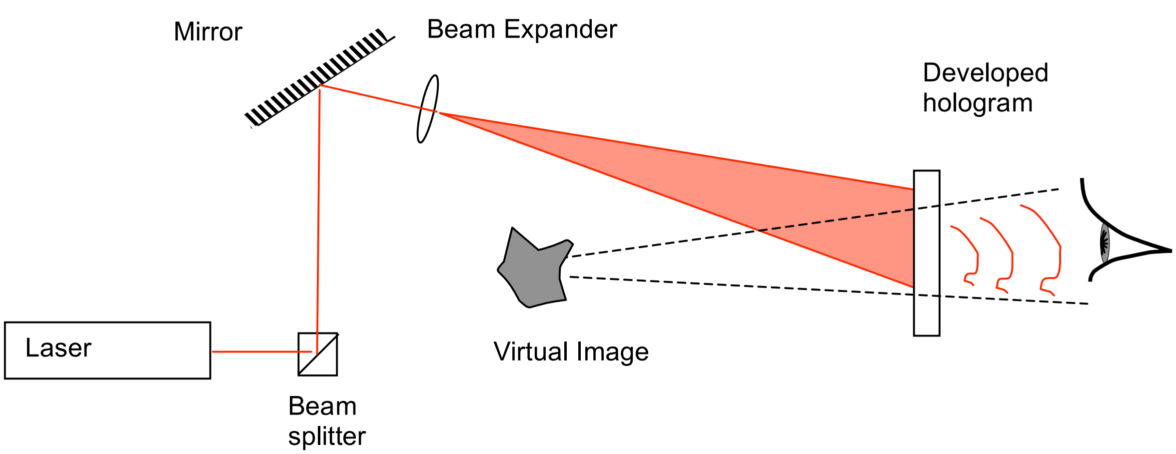


Figure 2 - To view the image, illuminate the developed hologram with a replica of the reference beam. The virtual object appears behind the film, at the original location of the object.

Procedure:
NOTE: This procedure assumes the use of PFG-03M film plates and JD-4 developer, available from Integraf (http://www.holokits.com/). If you use different film or developer, consult the manufacturer's instructions.

Setup:

1. Pour enough developer (equal parts A and B) into one developing tray to cover a film plate (around one half inch deep). Pour bleach a similar amount of bleach into a second tray. Fill a third tray with water only and add a few drops of Photoflo. Have a source of running water nearby. (If no running water is available, a large bucket of clean tap water will do.)
2. Arrange the counter so the film plates and developing trays are readily accessible. Clear away any other objects. Remember, you will be developing the film in the dark!
3. Ensure that the base for the laser and components is solid and free from vibrations. The optical breadboard should be placed on damping material, such as packing foam or neoprene mats or balls.
4. Set up the laser, microscope objectives, beam splitter, mirrors and object as shown in Figure 1. Use a string to measure the distance from beam splitter to mirror to plate and from beam splitter to object to plate. The two distances should be equal to within about a centimeter for best fringe contrast.
5. Block the reference beam and make sure the cleanest and brightest portion of the object beam is completely illuminating the object. Block the object beam and be sure the cleanest and brightest portion of the reference beam illuminates the film position. The reference beam must not strike the object.
6. Place a cardboard “shutter” in front of the laser.

Exposure:

1. Turn off the lights. Remove one film plate from the box. Close the film box completely.
2. Place the film plate in its holder, emulsion facing the object. Be sure it is secured and will not move during exposure.
3. Wait a minute or two (don’t touch the table) before exposure. Lift the shutter part way, so that the laser light is still blocked, and wait another minute for the vibrations to die out. Lift completely to expose the plate for about 8 seconds. (The actual time will depend on a number of factors, and is best determined through experience!)

Development:

1. Develop until about 80% opaque. If you have an optical filter for comparison, the film plate should be about 2.0 OD.
2. Rinse about 30 seconds in running water.
3. Bleach until clear. (You may turn on the room lights after bleaching)
4. Rinse one minute in running water.
5. Soak 2 minutes in the Photoflo solution and air dry. The hologram will not be visible until it is fully dry.

Viewing:

Place the developed film plate in its original position in the hologram construction set up. Remove the object or block the object beam. Look into the plate toward the original object position to view the image.

Conclusion:

Describe the difference between your hologram and a photograph of the object. What are the limitations on the size of the hologram object?

Explorations/Applications:

1. You can also make a transmission hologram with a single beam, by placing the object in front of the film, and off to one side, rather than behind the film as with a reflection hologram. For details see www.holokits.com.
2. Transmission holograms lend themselves to many interesting applications. For example, if the object is exposed twice (a double exposure), microscopic movements of the object will be revealed as dark lines across the image. Distances on the order of half the wavelength of light may be measured by this technique.
   Once you have mastered the two-beam method, try a double exposure hologram of an object that can be moved by micron amounts. A sand-filled soda can is one possibility; place a heavy weight (such as a lab kilogram weight) on top of the can for the second exposure.
   A second (more difficult) technique is to place the developed film plate in exactly the same position as it was during exposure. Look through the hologram as the object is deformed. Aluminum blocks used as objects deform measurable when heated with a hair dryer or heat gun.