Physics 428

Applied Optics

Laboratory Manual

Department of Physics

Western Illinois University

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Physics 428 ***Applied Optics***

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Lab Report Guidelines

Students are required to read the lab manual and collect their questions before coming to the lab. Each student should have a notebook for the lab. Please bring with you some common stationeries to the lab, such as a pen, a calculator, a flash drive, and a camera.

Laboratory report for each experiment is due in one week following the date of the completion of the experiment, unless otherwise arranged. No absences from the lab or late lab reports can be accepted, except for pre-approved, documented, and extenuating circumstances.

All text portions of the lab reports should be prepared using Microsoft Word or a compatible word processor. All graphs in the lab reports should be prepared using Microsoft Excel or a compatible graphing program. Hand-drawing diagrams for the lab should be attached to the lab report. If you use a photo, please crop the photo so that only necessary information is shown. The lab report should be close to a research paper format. Please read some papers displayed in front of the Physics Office and study the general format of writing a scientific paper. Please check for grammatical or spelling mistakes in your lab report before submission. You should submit a printed hardcopy.

All lab reports should have the following organizational structure with all six parts. The framework described here is intended to help you in professional writing for the preparation of conference presentations and research papers in experimental physics.

1) Title page — Title of that lab experiment, date of completion of the lab, your name, group members' names, course number, and instructor for that lab.
2) Introduction — Explain the purpose of the experiment and possible applications of interest according to your understanding.
3) Background theory — Include and explain any relevant background physics concepts and mathematical equations used in the experimental analysis and data collection.
4) Experimental details — Describe the procedure of how you do the experiment. Include a complete description of the instrumentation used and the manner in which you used it. Identify the strengths and weaknesses of the experimental setup, including any special cautions observed, and any applicable sketches or photos of the equipment details and arrangement. Include demos performed by the instructor.
5) Results and discussion — Present your experimental findings, along with relevant data tables, data printouts, graphs, spectra, or images obtained, along with any analysis performed, and interpret your data in light of the theory developed in part

3. Answer any questions that are raised in the lab manual. If the lab consists of several experiments with different objectives, it is suggested that each experiment have its own part 4 and 5 together in the lab report.

6) Conclusions — Summarize the major findings of your experiment. Explain any errors incurred or discrepancies with theory and identify where further work may be applicable.

Students are encouraged to discuss lab problems with the instructors, the classmates or any other persons. However, all lab reports submitted for a grade should be substantially from the student himself. Any cited work should have a reference. Plagiarism from the lab manuals, others' lab reports, published work, or the internet will result in immediate rejection of the lab report.

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Optics Lab Safety

1. Laser beams are in general hazardous to your eyes. **Please do never look at laser beams directly, including the reflected, refracted and specularly scattered laser beams.** Looking at the diffusive scattering of *our* laser beams on a piece of paper should be limited to a minimized time. Goggles are required when using high-energy lasers.
2. Please make sure that the laser beams do not hit on any other persons when you are manipulating lasers.
3. Most optical elements are delicate and surprisingly expensive. Please be careful in handling optics. Do not touch the surfaces of the optical elements. Do not breathe or talk to optical elements.
4. Please report damages of optical elements and instruments to the instructor.
5. Please shut off the lasers and other instruments, and sort the equipments after you finish the experiment.
6. Please have no food or drink, except water, in the optics lab.

1. Speed of Light

In this lab we will measure the speed of light using an apparatus that measures the time difference between the arrivals of a laser pulse reflected from two different places. The speed of light is obtained by dividing the spatial separation of the two laser pulses by their temporal separation. Although now the speed of light has been defined as a constant, this lab gives us experience on how to measure the time information of laser pulses, or in general the time information of electronic signals, which is useful in our future study.

1) Speed of light [Room 310]

A diagram of the experimental setup is shown in Fig. 1.

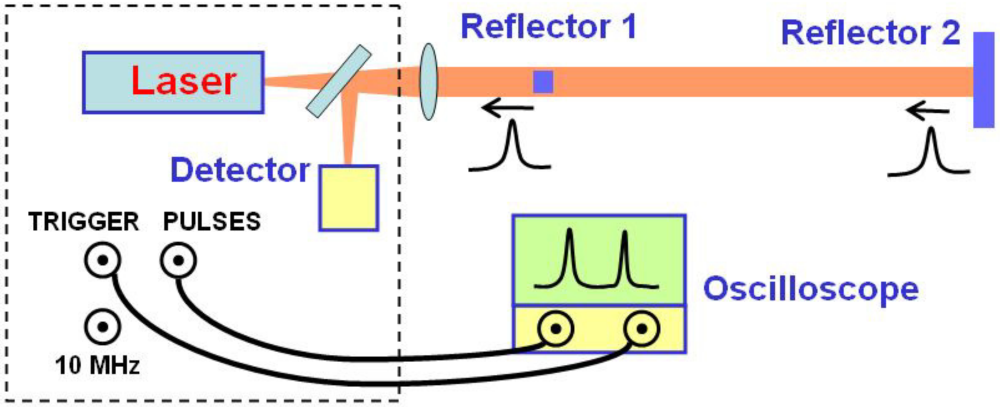


Fig. 1 Setup of measuring the speed of light

The apparatus provides the following three signals:

1) The detector signals for the two reflected laser pulses. The time difference between the two laser pulses is measured by observing the signals on an oscilloscope.

2) A trigger signal that has been synchronized to the laser pulse. This signal is used to trigger the oscilloscope.

3) An internal 10 MHz signal for the purpose of time calibration on the oscilloscope. Because the oscilloscope currently in use (Tektronix 2213A) has a bandwidth of 60 MHz, this 10 MHz signal is not used in our experiment.

You are assumed to have the basic knowledge of how to use an oscilloscope. If you are not familiar with the oscilloscope, please see the instructor on how to find and display signals on it. Please connect the cables to the oscilloscope. First please use only the larger reflector (reflector 2 in Fig. 1) and find the signal of the reflected light pulse on the oscilloscope. If the signal is too weak to be observed by the oscilloscope, you can adjust the position of the large lens so that the laser beam is better collimated, or slightly focused at a far distance, but usually this is not needed. Please measure the FWHM (full width at half maximum) and repetition rate (frequency) of the signal. The repetition rate of the laser pulse is not important in this experiment, but a measurement of the repetition rate is a good practice on how to use an oscilloscope. Special care must be taken when reading the time scale on the oscilloscope. First, the time scale is variable (and is thus not defined) if the time knob is not locked. Therefore please make sure that the time knob is locked when doing an actual measurement of time. Second, the time resolution is 10 times better when the knob is pulled out, e.g., 0.1 μs /div is actually changed into 0.01 μs/div.

The FWHM value of the signal can be thought as the "*pulse duration*" of the laser pulse. It is in fact the duration of the electronic signal produced by the laser pulse. From this pulse duration please estimate the minimum distance between the two reflectors that is required to produce a distinguishable pulse pair, i.e., if the two pulses do not overlap, at least how far they should be separated in space. Remember that one of the laser pulses travels a round trip between the two reflectors. Write down the pulse duration and the estimated minimum distance between the two reflectors. Explain how you estimate this distance. Please check with the instructor before you move on.

Now please move the larger reflector to a distance that is sufficiently longer than the estimated minimum distance, say, more than 2 times. Insert the smaller reflector (reflector 1 in Fig. 1) into the laser beam at a place after but not far from the big lens. It is better to place the small reflector directly on the table rather than on the optical rail that holds the laser, because later we need to fine tune it across the laser beam. You will see two distinct pulses on the oscilloscope. Please use a time resolution as high as possible, while keeping both pulses being simultaneously displayed on the range of the screen. In order to accurately measure the time difference between the laser pulses, the two signals should be separated far enough on the oscilloscope. This is done by simply increasing the distance between the two reflectors. An example of two distinct pulses observed on the oscilloscope is shown in Fig. 2. Please adjust the position of the larger reflector along the laser beam and **make sure that the two signals are well separated in time**, i.e., they do not have significant overlap even at their pedestals.

The time response of the photo-detector is dependent on the intensity of the light it receives. Therefore for an accurate time measurement one should always **make sure that the two reflected pulses have almost the same signal height** on the oscilloscope. This can be done by finely moving the small reflector across the laser beam to adjust the amount of light reflected to the detector.

In your lab report please sketch the experimental setup and the pulses you observed on the oscilloscope. You can also use photos, which may save you time. However, if you use a photo, please make sure that 1) you crop the photo so that only necessary information is shown, and 2) you label the main items and mark your major discoveries on the photo or describe them in the text.

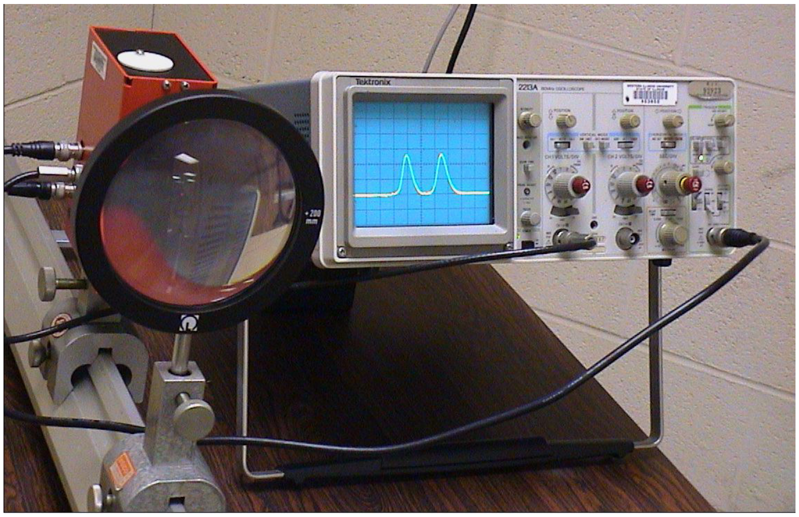


Fig. 2 Two separate signals for the reflected laser pulses

Now you can measure the spatial distance and the time difference between the two laser pulses. Please describe how you measure the spatial distance and the time difference. Calculate the speed of light. Determine the instrument reading uncertainties of your distance and time measurements, and the subsequent uncertainty of the calculated speed of light. Describe how you obtain these uncertainties.

An example of error estimation for this experiment is shown as follows. Suppose distance $d = 2 \times 12.5$ m $= 25.0$ m, time $t = 8.3 \times 10^{-8}$ s, speed $v = d / t = 3.0 \times 10^{8}$ m/s. The uncertainties will be $\Delta t = (0.5 \text{ div}) \times (10^{-8} \text{ sec/div})$, $\Delta t/t = 6\%$. $\Delta d = 20$ cm, $\Delta d/d = 1\%$. $\Delta v/v = [(\Delta d/d)^2 + (\Delta t/t)^2]^{1/2} = [(1\%)^2 + (6\%)^2]^{1/2} = 6\%$. $\Delta v = 0.06 \times 3.0 \times 10^{8} = 0.2 \times 10^{8}$ m/s, $v = (3.0 \pm 0.2) \times 10^{8}$ m/s. We need to round uncertainties to one significant figure. Also the number of decimal places in the magnitude must agree with the decimal place of the uncertainty.

Please repeat the measurement using at least **five different distances**. If possible, you can place the large reflector in the hall way, or in front of the door opposite to our lab, so the separation of the two light pulses can be maximized. Please calculate the average value of the speed of light. Be sure to write down the values of all measurements and the associated uncertainties. Compare the instrument reading uncertainty to the standard deviation of measurements, and use the larger one as the final uncertainty.

Additional Questions:

1. In our experiment, why do we need to place the larger reflector as far as we can?
2. Why do we use diffusive reflectors instead of specular mirrors?

2. Refraction and Reflection

In this lab we will observe the displacement of a light beam by a parallel plate due to refraction. We will determine the refractive index of some liquids from the incident and refractive angles. We will also observe the total internal refraction phenomenon and measure the refractive index of a medium from the critical angle.

1) Refraction by a plate [Room 312]

Please first check the alignment of the magnetic optical bench and the laser beam to make sure that the laser beam is parallel to the center line of the bench. The procedure to do this is described below. Attach a white paper to an optical element holder. Mark the center of the open area of the holder on the paper, e.g., using a cross or a point. Place the screen close to the 0 cm end of the magnetic bench. Adjust the position of the head of the laser until the beam hits the paper at the mark. Now move the screen to the other end of the bench (at near 100 cm). Adjust the position of the tail of the laser, and the bench leveling screws if necessary, so that the beam again hits the paper at the mark. Repeat this procedure several times so that the laser beam always hits the mark on the paper whether the paper is close or far from the laser. Now we are sure that the laser beam is parallel to the center line of the bench.

Place the small rotating table on the bench with its center at approximately the 20 cm mark. Make sure that the table is flush with the two sides of the bench. The zero degree mark on the table should line up along the center line of the bench, and should be on the side toward the laser. If not please ask the instructor to make an adjustment. The top plane of the table is free to rotate. Make sure that the white arrow of the rotating table points to the 0° mark (Fig. 1).

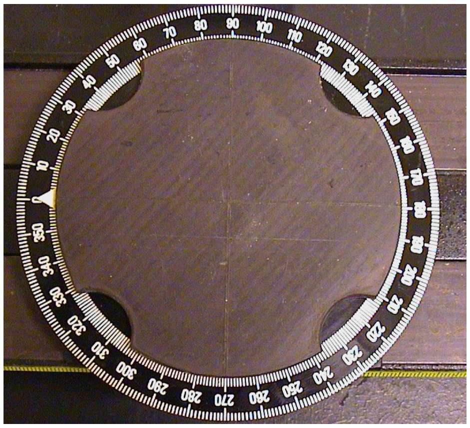


Fig. 1 The rotating table

Place a viewing screen on an element holder at the 100 cm mark of the bench. Make sure that the laser hits on the scale of the viewing screen so that we can later measure the displacement of the laser beam (Fig. 2).

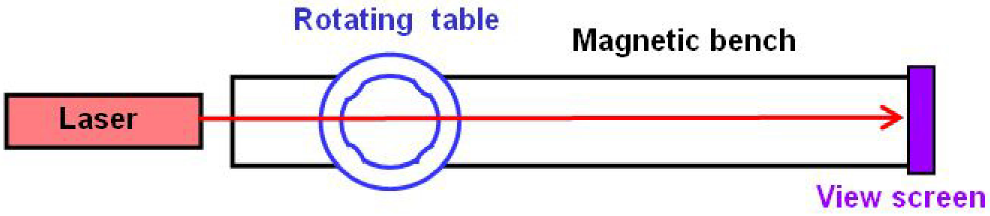


Fig. 2 Schematics of the apparatus

Place an acrylic plate directly on the table so that the laser beam hits one of the optical surfaces at 0° incident angle. This can be done by rotating the acrylic plate (rather than the rotating table) and observe the reflected laser beam at the output point of the laser. The reflected beam should be very close to the output window of the laser. However, exact overlap between the incident and reflected beam should always be avoided. The surface of the acrylic plate should be along the 90º-270º diameter line of the small rotation table. You can let the laser beam strike somewhere on the right half of the front surface (viewed when facing it) of the acrylic plate, so that in later experiment the light can make more times of reflections inside the plate.

By observing the point at which the beam hits the viewing screen, determine if there is any displacement of the beam. If there is a displacement for normal incidence, this indicates that the two surfaces of the plate are not exactly parallel. For non-normal incidence a displacement of beam occurs as shown in Fig. 3. Also an angular deviation of the beam may occur if the two surfaces of the plate are not exactly parallel, as shown in Fig. 4.

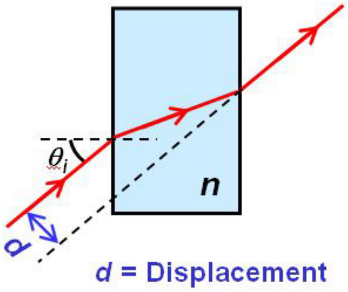


Fig. 3 Beam displacement in a parallel plate

Please do the following exercises:

a) Measure the displacement of the beam by the acrylic plate for the following angles of incidence: 10º, 20º, 30º, 40º, 50º, 60º. When you rotate the small rotating table please do it slowly so that the acrylic plate is not disturbed.

b) At the incident angle of 40º, determine how many reflected and transmitted beams you see. You may need to turn off the lights when looking for these beams. Make a sketch of these beams and explain where they come from.

c) At the incident angle of 40º, determine the angular deviation of the beam. You will need to measure the positions of the beam at immediately after the table, and at the 100 cm mark on the bench, without and with the plate on the table, and then use trigonometry to find the angle. Please include a sketch showing your measurements and show your calculations. Your result of the angular deviation may not be very accurate. However, it gives us the order of magnitude of how much the laser direction may deviate when passing through a normal parallel plate optical element. If your result is exactly 0°, please just mention that our apparatus is not able to measure a small deviation angle.

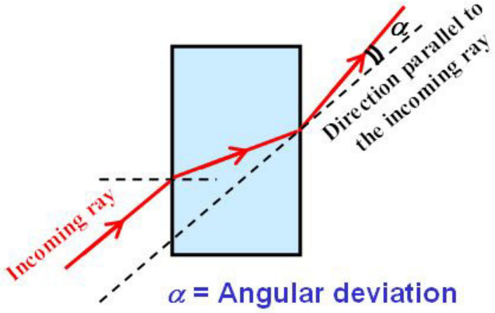


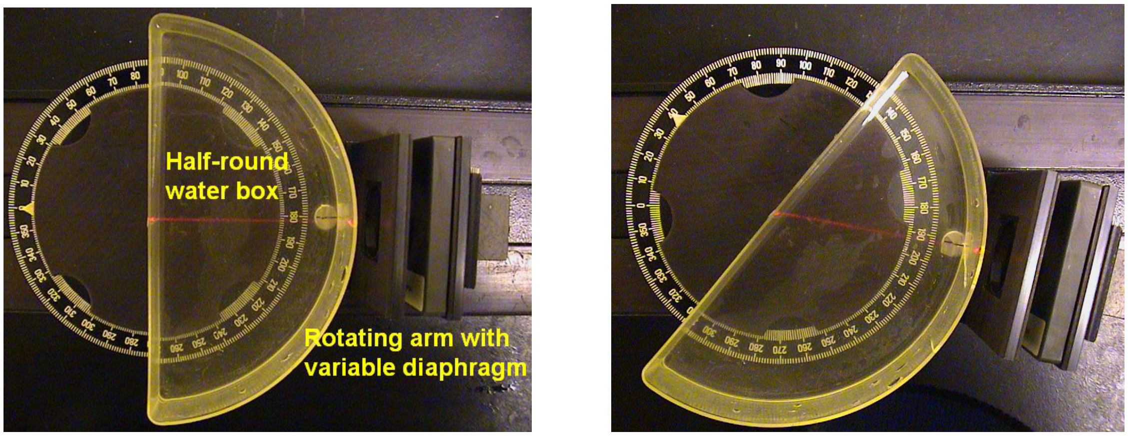
Fig. 4 Angular deviation from a parallel plate

2) Refractive index of liquids [Room 312]

Please remove the acrylic plate and place an empty half-round plastic box on the rotating table. Orient the box so that the laser beam hits on the center of the flat side of the plastic box with 0° incident angle. You may need to raise the box a little using two glass plates with magnetic stripes so that the laser beam strike on the surface of the box. Now rotate the box through the rotating table and note that the rotation has almost no effect on the beam. The displacement and deviation of the beam is very small regardless of the angle of incidence between the beam and the flat surface of the box. Why is the effect so small?

Turn the rotating arm of the table to 180°. This angle is read from a mark on the rotating arm. Insert a variable diaphragm onto the holder on the arm. Fine tune the position of the diaphragm by sliding the diaphragm on the holder until you get the maximum light output from the aperture. Be sure keep the arm always at 180°. Adjust the size of the aperture of the diaphragm so that the laser beam is barely passed.

Now place a half-round box filled with water on the table as shown in Fig. 5(a). Please be careful not to spill water on the table. The flat edge of the box should be along the 90°-270° line.



(a) (b)

Fig. 5 (a) Initial positions of the water box and the rotating arm, and (b) the positions of the box and the arm at 40° incident angle

Shift the box back and forth along the 90°-270° line until the laser beam passes through the diaphragm with the maximum output. The laser beam should now hit the flat side of the box around its center. Please avoid striking the laser beam exactly at the vertical mark line at the front surface of the box (if there is a line there), otherwise the light may be severely scattered. Rotate the table by 40° (read from the white arrow). The beam is now refracted at the air-water interface where it enters the box. However, the beam is not refracted as it exits the box. Why not? The angle of refraction can be obtained by rotating the arm so that the light exactly passes through the aperture of the diaphragm. The positions of the box and the arm in this case are shown in Fig. 5(b). Please read the angle of the rotating arm to ~0.25° accuracy. Determine the angles of incidence and refraction. You may need a sketch in order to get the angle of refraction. Please calculate the index of refraction of water. Your value should be close to 1.33. If not, think carefully about what is possibly wrong. Please check with the instructor before you move on.

Please do the following exercises:

a) Determine the angle of refraction for incident angles of 10º, 20º, 30º, 40º and 50º. Take a top view photo of the setup when the incident angle is 50º. Calculate the index of refraction for each case. Take the average of the five values of *n*.

b) (If we have time) Replace the water box by another half-round box filled with corn oil. Repeat the measurement of the refractive index at all incident angles.

3) Total internal reflection [Room 312]

Please configure the light box to produce a single light ray. Use the half-round solid optical element to observe total internal reflection. Input the light along a radius of the element. The reflected and refracted beam from the flat surface of the element can be seen as in Fig. 6. You may need to turn off the ceiling light in order to see them. Rotate the optical element carefully so that the ray reflects at the critical angle. Make sure that the input beam is always along a radius of the element. Since different colors of light have slightly different critical angles, let us use the red color of light as the representative ray because it appears stronger in the spectrum of our present light source. In addition, we use He-Ne laser in our future experiments, which happen to be red. Make a sketch of the beams and measure the critical angle using trigonometry first. Then confirm your number by directly measuring the angle using a protractor. Please calculate the index of refraction of the optical element using the critical angle you measured.

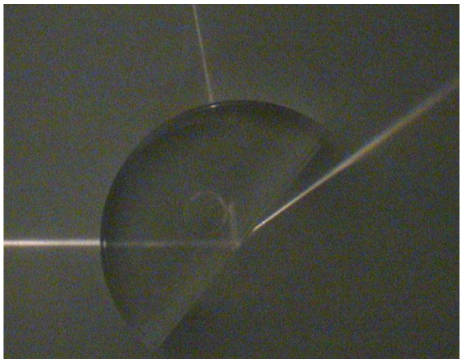


Fig. 6 Reflection and refraction from a half-round optical element

Additional Questions:

1. Please draw a sketch of our setup of measuring the refractive index of water. From your sketch explain how you measure the angle of refraction using the position of the rotating arm.
2. In our total internal reflection experiment, when you are gradually increasing the angle of incidence, which color of light is first subject to total internal reflection?

3. Laser Beam Manipulation

In this lab we will learn how to manipulate laser beams using prisms and lenses. A laser beam can be steered, split, expanded or collimated using these optical elements.

1) Beam steering using prisms [Room 312]

As in previous labs, please first make sure that the laser beam is parallel to the center line of the bench. This will make our experiment much easier. Position a 45-45-90° prism on the small rotatable table, or a wood plate, on the bench as shown in the figure below, so that the laser beam is redirected at right angles to its original direction. You may need a metal plate to raise the prism. Please handle the prism with care, and avoid touching its optical surfaces. According to your observation, how does the intensity of the redirected beam compare to that of the original? Why isn't there a beam exiting from the hypotenuse side of the prism? Try rotating the prism and see if you can find other prism orientations that permit a beam to exit from the hypotenuse side. Draw a figure of the laser beams you have observed, and show their paths.

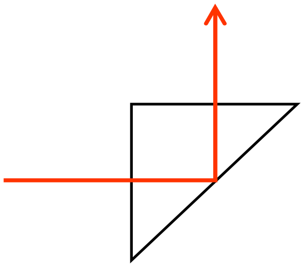


Fig. 1 Redirection of a laser beam using a prism

Now use a second prism to redirect the beam parallel to its original direction as shown below. What are the advantages and disadvantages of this method of displacing a laser beam compared to the parallel plate method used in the previous lab?

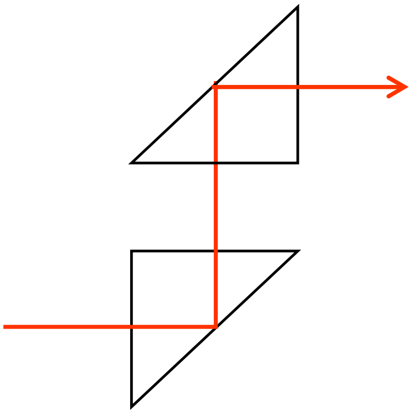


Fig. 2 Displacing a laser beam using two prisms

2) Beam steering using lenses [Room 312]

Remove the prisms from the bench. Place the f = -22 mm negative lens on an element holder and position it in the laser beam close to the laser output window. Note that this lens causes the laser beam to expand. Move the lens slightly in one direction (up, down, right, left). What happens to the beam — does it move in the same direction as the lens, or in the opposite direction? This is called beam steering and can be used to aim the beam. Please show a ray diagram to explain this result.

Replace the -22 mm lens with the f = +18 mm lens. Note that the beam is again expanded. Move the lens in various directions and observe the effect on the beam. Is the beam steered in the same direction or the opposite direction? Please show a ray diagram to explain this result.

3) Beam splitting [Room 312]

Sometimes it is necessary to split a laser beam into two or more parts. This is done using a beam splitter. Position the thick glass plate so that the laser beam strikes its face at a 45° angle. Note that the beam is split into several reflected and refracted beams. Sketch the directions of the original beam and of all the reflected and refracted beams. Note on your sketch the relative intensities of each beam. Can you determine the origin of each reflected and refracted beam?

What happens when a thin glass plate is used?

4) Beam expansion [Room 312]

With no lenses in the path of the laser beam, measure the beam diameter of the unexpanded beam close to the laser (it should be approximately 1-2 mm). Also measure the beam diameter where the laser strikes the wall of the room. Is the beam collimated (i.e., does its diameter remain constant)?

Now place the -22 mm focal length lens in the beam close to the laser. What is the beam diameter at the wall? Repeat using the +18mm lens, the +136 mm lens, and the +252 mm lens. What do you conclude about the expanding power of these lenses? Do negative lenses work better than positive lenses? Does the expanding power of a lens depend on its focal length? Explain your conclusions using ray diagrams.

5) Beam expansion and collimation [Room 312]

You found in the previous part that the laser beam with no lenses in its path was *not* collimated. (A laser beam is collimated when its diameter is constant.) However, we can use two methods, i) two positive lenses, or ii) a negative lens and a positive lens, to produce an expanded and collimated beam. Please first discuss with your partners on how you can achieve this. Please draw a sketch on how you are going to place the two lenses in each case, and how many times the beam size will be expanded. Please let the instructor have a look at the sketch.

Please choose the two lenses that will produce the maximum expansion in each of the two methods. Adjust the position of the lenses so that the beam is steered directly down the center line of the bench. To ensure that the beam is collimated, you must measure its diameter just after it passes through the second lens and then again at the wall. By comparing the two diameters, you will be able to determine if the beam is collimated. If it is not, you will have to fine tune the distance between the lenses.

Please fill in the following table by recording the focal lengths of each lens you used, the distance between them, and the diameters of the expanded and collimated beam. You also need to measure the diameter of the initial unexpanded laser beam. Does the magnitude of expansion agree with your theoretical predictions?

	f_1	f_2	Distance	Unexpanded beam diameter	Expanded beam diameter	Expansion ratio	$\lvert f_1+f_2\rvert$	$\lvert f_2/f_1\rvert$
Positive +positive								
Negative +positive								

4. Dispersion

In this lab we will explore how the index of refraction of a material depends on the wavelength of the incident light. We first study the phenomenon of minimum deviation of a prism. We then measure the wavelengths of the light passing through several narrow band interference filters, and determine the index of refraction of a prism at each input light wavelength using the minimum deviation method.

1) Minimum deviation of a prism [Room 310A]

Let us first study the phenomenon of *minimum deviation* of a prism and learn how to measure the refractive index of a material using this method. In the minimum deviation condition, the deviation angle between the initial incident light and the final refracted light is minimized. In this condition the directions of the incident and the output lights should also be symmetric with respect to the prism. The geometry of minimum deviation is shown in the figure below.

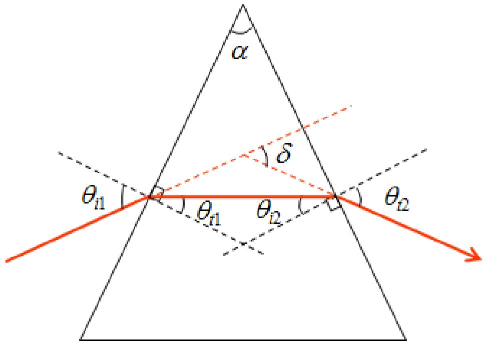


Fig. 1 Minimum deviation condition of a prism

The index of refraction of the prism at the input wavelength can be calculated using equation 5.54 in the text, $n = \sin\frac{\delta_m + \alpha}{2} \Big/ \sin\frac{\alpha}{2}$. Here δ_m is the angle of minimum deviation, and α is the angle of the prism.

Now please use the plastic 60° prism and a single ray from the light box to observe the phenomenon of minimum deviation. Does this prism separate the white light into its spectral colors? Make a sketch in your lab notebook showing the prism and the ray of light at minimum deviation. Use this sketch to measure the angle of minimum deviation and then calculate the index of refraction of the prism. Please use the red color in the refracted light as the representative light ray.

Now try to obtain minimum deviation with a 90º-45º-45º prism, using the right angle for refraction. Draw one or more sketches of your attempts and use them to explain why minimum deviation cannot be achieved for this prism.

2) Dispersion [Room 310A]

Please note that the filters on the wheel and the monochromator used in these dispersion measurements are delicate and expensive. Please be *careful* in handling them. Never touch the optical surfaces of the filters or the slits of the monochromator.

In order to obtain different wavelengths of visible light, we will use a series of narrow band interference filters. All you need to know about these filters at present is that each of them permits a different narrow range of wavelengths to pass through. Their operating principle will be explained in future classes. The filters are fastened in position on a filter wheel with a dial that can be used to select the various filters. When the dial is in position #8, there is an open slot on the wheel and the light passes through without encountering any filter. Position #1 contains a blank element and no light passes through. The other six positions contain filters that pass visible wavelengths.

Thanks to the investment of our department, we now have all the optical elements mounted on their solid holders. The whole system is mounted on a large aluminum breadboard, as shown in Fig. 2. Please place the white light source and the filter wheel in position. Turn the filter wheel to position #7. Look through the filter wheel at the light. You should see a red-colored light bulb. The red color corresponds to the wavelength being passed through this particular filter. Turn the dial on the filter wheel and observe the other colors passed through the filters.

You will now use a monochromator to determine the peak wavelength passed by each filter. The operation of the monochromator will be discussed later. Its function is to pass a narrow band of wavelengths that can be varied continuously from infrared to ultraviolet by turning a micrometer dial. The focal length of the lens is about 50 mm. Adjust the white light bulb so that its image from the lens is almost vertical. Especially please make sure that the light enters the monochromator through the center of its entrance slit, so that the energy of the input light is maximized.

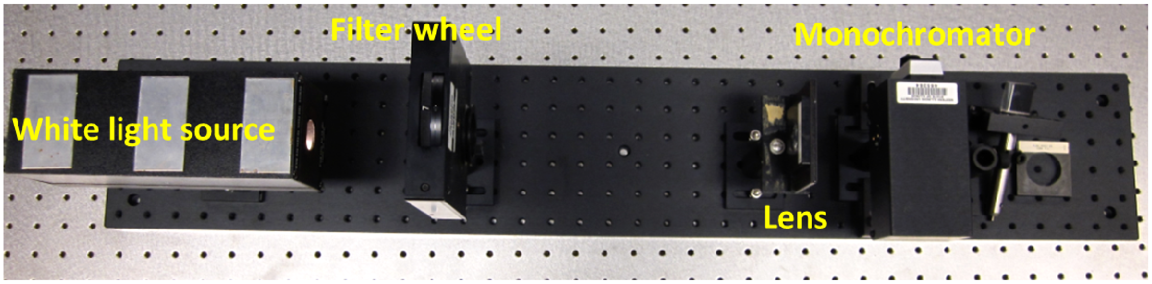


Fig. 2 Experimental setup for measuring the transmission wavelengths for the narrow band interference filters

With the filter wheel set to position #8, which is a blank opening providing a white light source, adjust and optimize the positions of the monochromator, the filter wheel, and the light source so that you can see an image of the bulb when looking back through the exit slit of the monochromator. Now it is a good time for us to relate light wavelengths with spectral colors. Please keep the filter wheel at position #8. Please observe the colors of the light by looking through the exit slit of the monchromator while turning the monochromator dial from 700 nm to 400 nm at 50 nm/step. Remove the post stand at the end of the breadboard when necessary, so that it won't bother you. Please use some refined words to fill in the following table to describe the colors you observed for each wavelength. It is useful to remember them by heart.

Wavelength (nm)	Color
700	
650	
600	
550	
500	
450	
400	

Now set the filter wheel to place filter #7 in position. Turn the monochromator micrometer dial slowly until you begin to see light coming through the system. In the following table please record the peak wavelength, which is the wavelength of the brightest light passed, as well as the shortest and longest wavelengths passed by the filter. Repeat this for the other five filters. List the peak wavelength as well as the shortest and longest wavelengths passed by each of the filters in a table. The peak wavelengths will be taken as the typical wavelengths passed by the filters.

Filter	Color	Peak wavelength	Minimum wavelength	Maximum wavelength
#7				
#6				
#5				
#4				
#3				

#2				

Now remove the filter wheel and the monochromator. Use the lens provided (currently focal length 238 mm) to project a clearly focused image of the bulb filament onto a piece of paper attached on a viewing screen. This is done by finely adjusting the position of the viewing screen. Alternatively, you can use a piece of paper attached on the wall as a viewing screen. In this case finely adjusting the distance between the breadboard and the wall will make a clear image of the bulb filament. Please make sure that the light beam is parallel to the longer edge of the breadboard, and is perpendicular to the viewing screen. This will later make the measurement of the deviation angles of the light beams easier. Please mark the location of the undeviated beam on the viewing screen. Now place the large 60° prism on a rotational stage near to the end of the breadboard (as far from the light source as possible). Please rotate the prism finely by turning the rotational stage (or the rod) until you see a "rainbow" or spectrum formed on the viewing screen. Rotate the prism carefully until the condition of minimum deviation of the spectrum is attained. Please ask the instructor to have a check after you finish this step.

Now place the filter wheel in the light path between the lens and the prism and set the dial to filter #7. You may fine tune the distance from the lens to the wall so that this monochromatic image is optimized. Measure the minimum deviation angle for this wavelength of light. Remember that the deviation angles are measured from the original location of the filament image on the viewing screen. Instead of trying to measure angles directly, it is easier and more accurate to measure appropriate distances and then use trigonometry to determine the angles. You may need to block the stray light using a piece of black cloth. Please show how you measure the angle of minimum deviation with a sketch. Repeat the measurement of the minimum deviation angles for other filters.

Please calculate the index of refraction of the prism at each wavelength of light using the equation mentioned above. Draw a plot of index of refraction versus wavelength. How do your results compare to the attached dispersion data?

Additional Questions

1. Based on Equation 5.54 in the textbook, explain why the right angle of a 90º-45º-45º prism cannot be used to measure the refractive index of a material with $n \approx 1.5$ using the minimum deviation method.

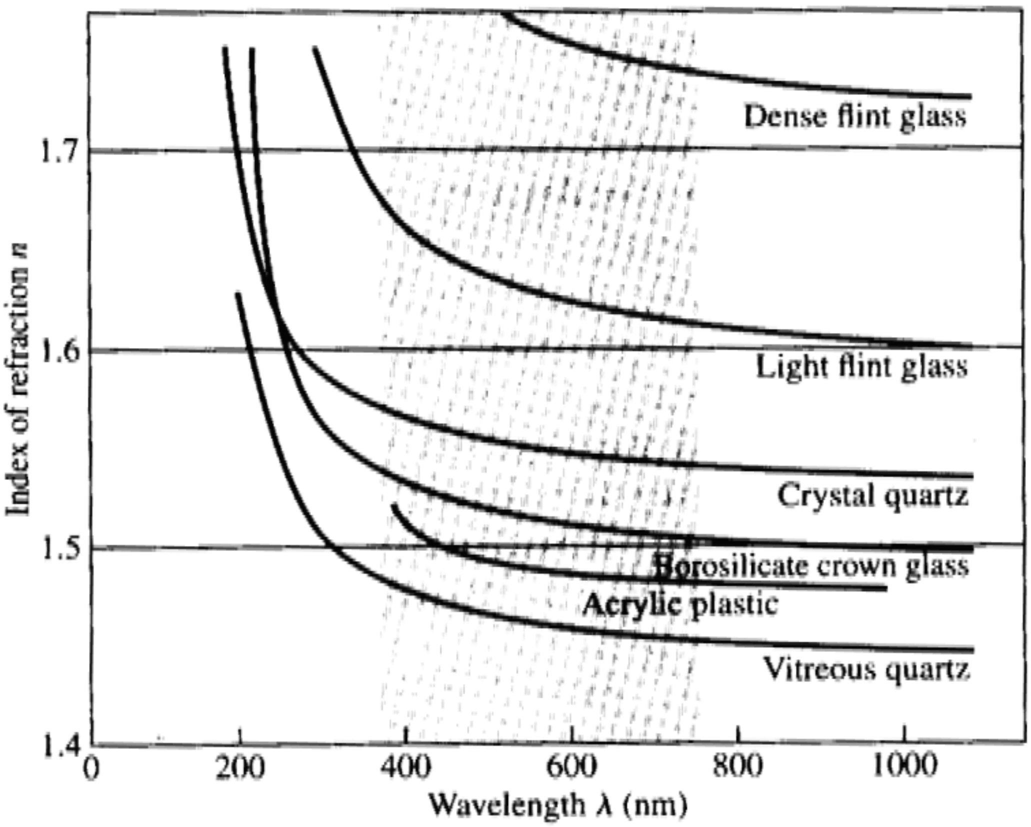


Figure 3.40 The wavelength dependence of the index of refraction for various materials. Note that while λ goes up toward the right, ν goes up toward the left.

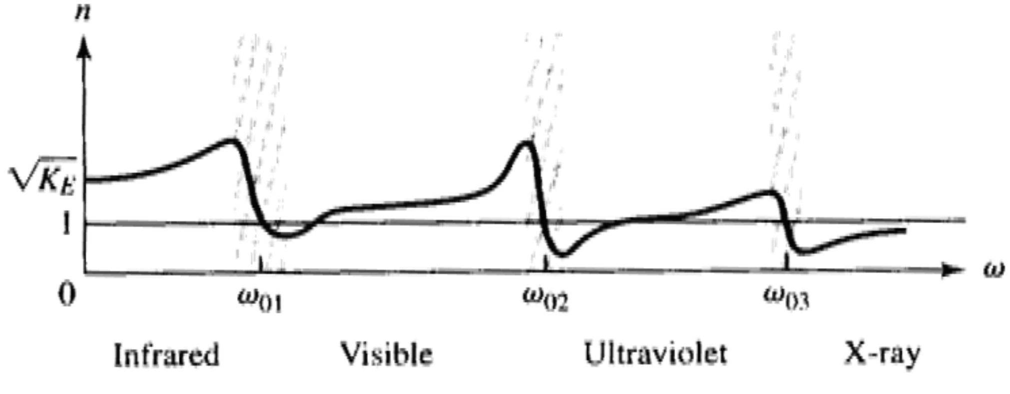


Figure 3.41 Refractive index versus frequency.

5. Spherical Mirrors and Lenses

In this lab we will study the focusing and imaging of spherical mirrors and lenses. We will measure the focal lengths of lenses using several different methods. We will observe the imaging properties of mirrors and lenses at different object distances.

1) Spherical mirrors [Room 312]

a) Large spherical mirror

Please examine the images formed by the large spherical mirror, from both the concave and the convex sides, and verify that the image properties agree with the predictions of Table 5.5 (Page 189 of the text, attached here). In each case please describe qualitatively (no numerical data needed) and briefly what object you use, and what you see about the image.

b) Spherical mirror elements

The light box is used in conjunction with two spherical mirror elements to allow you to actually see what happens to light rays as they reflect from the mirrors. Please configure the light box to produce three parallel rays of light. If you lay a piece of paper on the table next to the box and place a mirror element on the paper, you will see the paths of the incident and reflected light rays on the paper. Please see Fig. 1 for an example. A pencil can be used to trace an outline of the element and to draw the paths taken by the incident and reflected light rays. You can thus make a permanent record on the paper of both the light rays and the optical elements.

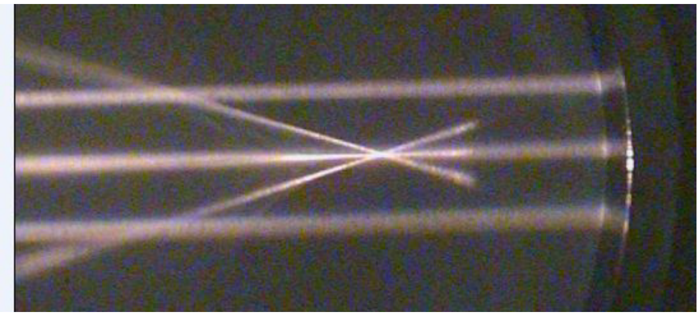


Fig. 1 Light focusing by a spherical surface

Please use the reflected light rays to determine the focal lengths of one of the two mirror elements, in both of their convex and concave modes. You will thus need to determine *four* focal lengths. Please attach copies of the ray tracing diagrams recorded on paper for each of the four cases.

For each of the four cases, please use your drawings to determine the radius of curvature of the mirror and explain how you did this. Please note that for each mirror element the convex and concave mode may have different radii of curvature because the element has a non-negligible thickness. Does the focal length have the correct relationship to the radius of curvature of the mirror?

2) Lens focusing [Room 312]

Please configure the light box to produce four rays. Observe the paths of light rays passing through the thin positive or negative lenses. An example is shown in Fig. 2. In each case please make a drawing on paper of the lens and the light rays you used.

Fig. 2 Light focusing by a thin positive lens

Please use the refracted light rays to measure the focal lengths of the thin positive and negative lenses. Include a copy of the drawings used to determine the focal lengths.

Please determine the radius of curvature of each lens and calculate the focal length using the lens-maker's equation (Eq. 5.16 in the text) and the refraction index determined by the method of total internal reflection (see Lab #2).

What happens when you combine the thin negative and positive lenses to form one single lens?

Now please use a thick lens. Does the thick lens have a true focal point? Please explain.

3) Thin lens imaging [Room 312]

In this part of the experiment we will study two positive lenses (labeled as positive 1 and positive 2) and one negative lens (labeled as negative 1). Later you will be asked to evaluate the focal lengths of these lenses. They are actually written on the bottom of the lens holders. However, they are written in disguised Japanese. You may need much more efforts to decode them than measure the focal lengths using the optical methods described below.

a) Positive and negative lenses

Please hold each of the lenses, one at a time, about 12 inches from your eyes and observe an object on the other side of the laboratory (for example, the lab door). Move the lens close to your eye and then move it as far away as you can. Negative lenses should produce an upright image no matter how far from your eyes the lens is positioned. Positive lenses should produce an upright magnified image of the object when held close to the eyes, and an inverted minified image when held far away from the eyes. Verify that the lenses behave properly.

b) Focal lengths of positive lenses

i) Infinite object distance method

When a positive lens forms an image of a very distant object, the image distance is equal to the focal length of the lens. Determine the focal lengths of positive lenses 1 and 2 by forming a clear image of the farthest ceiling light in the hall way on a screen (a small white card works nicely) and measuring the distance from the lens to the screen. Give the focal lengths of lenses 1 and 2 determined using this method. What sources of error are inherent in this method?

ii) Thin lens equation method

We can determine the focal lengths of lenses 1 and 2 using the thin lens equation. Please use the lighted crossed-arrow from a light source as the object, and form the image of the crossed-arrow on a white screen. The object, lens, and screen should all be placed on the 1.2-meter optics bench. Please place the lens at some distance from the object and move the screen until a clear image is formed. An image is clear when you can see the tiniest detail on it. Measure the object and image distances, and use the equation $1/s_i+1/s_o=1/f$ to calculate the focal length. Please fill your data into the table below.

Lens	s_o	s_i	f
#1			
#2			

Please repeat the measurement for three times, using different object distances. Show how you calculate each focal length. Give the focal lengths of lenses 1 and 2 determined by this method. Please compare the focal lengths obtained by this method to the values found by the infinite object distance method.

c) Focal length of a negative lens

We can use one of the positive lenses combined with the negative lens to determine the focal length of the negative lens. The method is described as follows. First please use only the positive lens and form a real image of the crossed-arrow, and record the position of the image. Let us call it image I. Next please insert the negative lens in between the positive lens and image I. Image I will now serve as a virtual object for the negative lens. Use the screen to find the image of this virtual object formed by the negative lens. It should be a real image, and let us call it image II. From the positions of the negative lens, image I and image II we can calculate the focal lens of the negative lens.

Please in your lab report briefly describe this method, show all original data and give the focal length of the negative lens you have determined.

d) Positive lens imaging

Now please use one of the positive lenses and verify the correctness of Table 5.3 (Page 165 of the text, attached here). Please fill in the following table to show each of the five cases in Table 5.3 you have tested. This table includes (if possible) the object distance you used, the image distance you found, the object height, the image height, the magnification, the nature of the image formed (real or virtual) and the orientation (erect or inverted) of the image. For the case of $s_o < f$ please look through the lens toward the object side and see if you can see an image. Please discuss on how well your data support Table 5.3 of the text.

$f =$ mm

Case	s_o	s_i	y_o	y_i	M	Real/virtual	Erect/inverted
$s_o>2f$							
$s_o=2f$							
$f<s_o<2f$							
$s_o=f$							
$s_o<f$							

Table 5.5 Images of Real Objects Formed by Spherical Mirrors

Concave

Object	Image			
Location	Type	Location	Orientation	Relative Size
$\infty > s_o > 2f$	Real	$f < s_i < 2f$	Inverted	Minified
$s_o = 2f$	Real	$s_i = 2f$	Inverted	Same size
$f < s_o < 2f$	Real	$\infty > s_i > 2f$	Inverted	Magnified
$s_o = f$		$\pm\infty$		
$s_o < f$	Virtual	$\lvert s_i \rvert > s_o$	Erect	Magnified

Convex

Object	Image			
Location	Type	Location	Orientation	Relative Size
Anywhere	Virtual	$\lvert s_i \rvert < \lvert f \rvert$, $s_o > \lvert s_i \rvert$	Erect	Minified

Table 5.3 Images of Real Objects Formed by Thin Lenses

Convex

Object	Image			
Location	Type	Location	Orientation	Relative Size
$\infty > s_o > 2f$	Real	$f < s_i < 2f$	Inverted	Minified
$s_o = 2f$	Real	$s_i = 2f$	Inverted	Same size
$f < s_o < 2f$	Real	$\infty > s_i > 2f$	Inverted	Magnified
$s_o = f$		$\pm\infty$		
$s_o < f$	Virtual	$\lvert s_i \rvert > s_o$	Erect	Magnified

Concave

Object	Image			
Location	Type	Location	Orientation	Relative Size
Anywhere	Virtual	$\lvert s_i \rvert < \lvert f \rvert$,	Erect	Minified

6. Interference

In this lab we are going to study various interference phenomena by observing their interference fringes and interference patterns. These phenomena include the thin film interference, the equal thickness interference, and the double slit interference.

1) Thin film interference [Room 310A]

The thin film interference patterns are produced by the superposition of the reflections from the upper and lower surfaces of a film. Please make a soap solution by adding a few drops of new dish detergent (or hand wash) into about 20 ml of water. A diluted solution may work better than a thick one. Dip the circular wire loop into the soap solution and pull it out slowly. Check if there is a soap film in the loop. If not, please try again. Hold the soap film horizontally and view it in the reflected light from the fluorescent lights. You may see only the reflected white light with a few colored swirls caused by interference. The film is too thick to show much interference.

Now please hold the film at an angle of about 45° to the vertical and view the light reflected from the film. One alternative way to do this is to lean the loop inside the cup as shown in Fig. 1. You may need a desk lamp for the light source. In a few seconds you should begin to see a pattern of color bands start to form. This is the *thin film interference*. The force of gravity pulls the soap film to the bottom of the loop and causes the upper portions of the film to become thin enough to produce an interference pattern. Please continue to view the film and observe the changes that take place. By convention purple or red is defined as the end of a band and the start of the next band in the interference pattern. In what order do the colors appear within the first and the second band? How does the density of the bands vary in space? How do the bands move? What causes the top of the film to be black? You may need to practice the experiment several times in order to get good fringes. Please take a photo of the fringes you have seen.

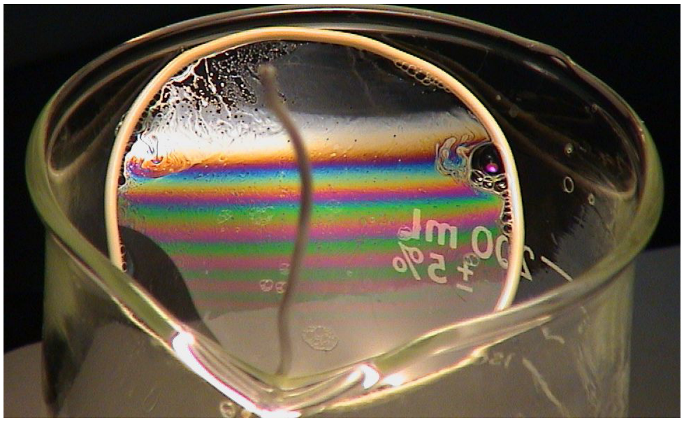


Fig. 1 Interference fringes from a soap water film

Interpreting the colors in white light interference requires some effort. A calculated interference color chart is given at the end of this lab, where although the colors are for crossed polarizers, they are the same for thin films. A good review paper is written by Hiroshi Kubota, *Progress in Optics* 1, 211 (1961). Dr. Wang is now recruiting a student who can write a thesis on the appearance of the colors in the interference of white light and its various applications.

2) Fringes of equal thickness [310A]

Please turn on the green viewing light. This is a mercury lamp with a green filter. It emits monochromatic light with a wavelength of 546 nm. For fun you can write your name on a piece of white paper using red ink, and then put it under the green light and see what color your name appears to be.

Please put the two circular "flats" together on the table top and position them so that you can see the green light reflected from them. A *flat* is a piece of glass that has been ground to have an extremely flat surface. Please do not touch the optical surfaces of the flats. The setup is shown in Fig .2. You should see interference fringes. These fringes are caused by the thin film of air between the flats, and are therefore *fringes of equal thickness*. Please press the two flats together and at the same time move them back and forth slightly. You should see the distance between the fringes increase. Why does this happen? If the fringes were perfectly straight, the two glass surfaces would be perfect planes. How flat are the surfaces? Describe how fringes of equal thickness could be used to determine the flatness of a piece of glass. Please take a photo of the fringes you have seen.

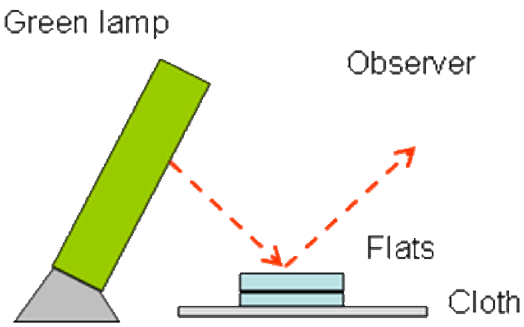


Fig. 2 Observing interference fringes from two flats

Now please put the two long and narrow rectangular flats together and view them in the green light. Again you should see fringes of equal thickness. How flat are the plates?

Position the plates at right angles to each other as shown in Fig. 3, and press them together until the fringes are quite wide. When necessary, press at the two ends of the upper flats and you should see circular fringes. These are called *Newton's rings*. They are caused by the slight curvature you produce in the upper plate when you press on its ends. You may need to shift or adjust the orientation of the upper plate in order to see the rings. If you see hyperbola lines, you may just flip the upper glass plate over to see the rings. Please take a photo of the Newton's rings you have seen.

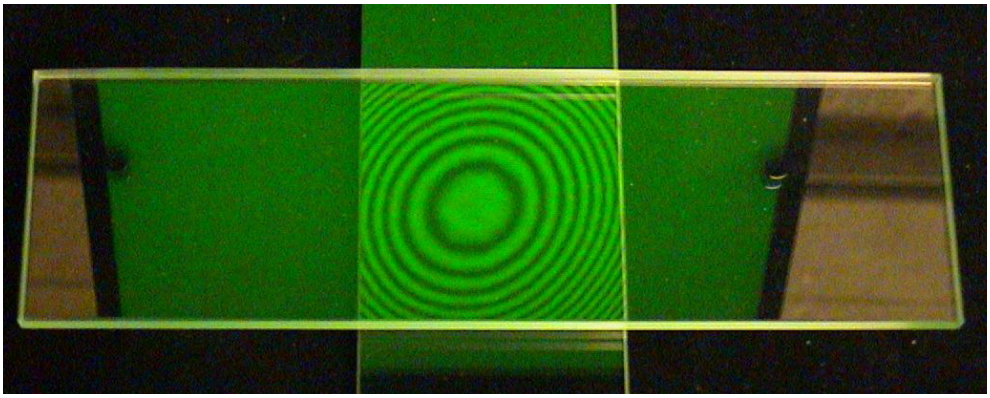


Fig. 3 Newton's rings from two flats

Now please position the two plates with their long axes parallel to each other and place a hair from someone's head between the plates at one end. The hair will cause the air film between the plates to take on a wedge shape. When necessary use two rubber bands to hold the plates in position. One band should be placed at the location of the hair and the other band should be placed at the opposite end of the plates. You should see closely-spaced parallel fringes perpendicular to the long axis of the plates. Please count the number of the fringes and use the information given on page 413 of the text (Eq. 9.41) to determine the thickness of the hair. You need a little ingenuity to count the number of fringes. Please describe how you count them.

Please take a photo of the fringes. Also please measure the hair thickness with a micrometer to verify the correctness of your results. Note that each division of the laboratory micrometer is 10 μm, and you need to include the effect of the incorrect zero point of the micrometer.

3) Double slit interference [310A]

Please use the unexpanded red He-Ne laser beam to produce a diffraction and interference pattern on the wall screen using the double slit that has a slit width of 0.04 mm and a slit spacing of 0.250 mm. Please take a photo of the pattern. Note that this pattern is a *superposition* of a single slit diffraction pattern and a two source interference pattern, as shown in Fig. 4. Please measure the distance between the interference minima. Is it close to $\lambda s/a$? Here a is the slit spacing and s is the distance from the slide to the screen.

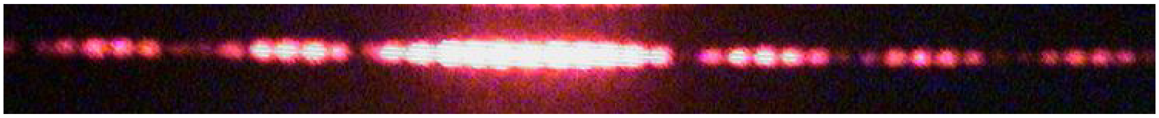
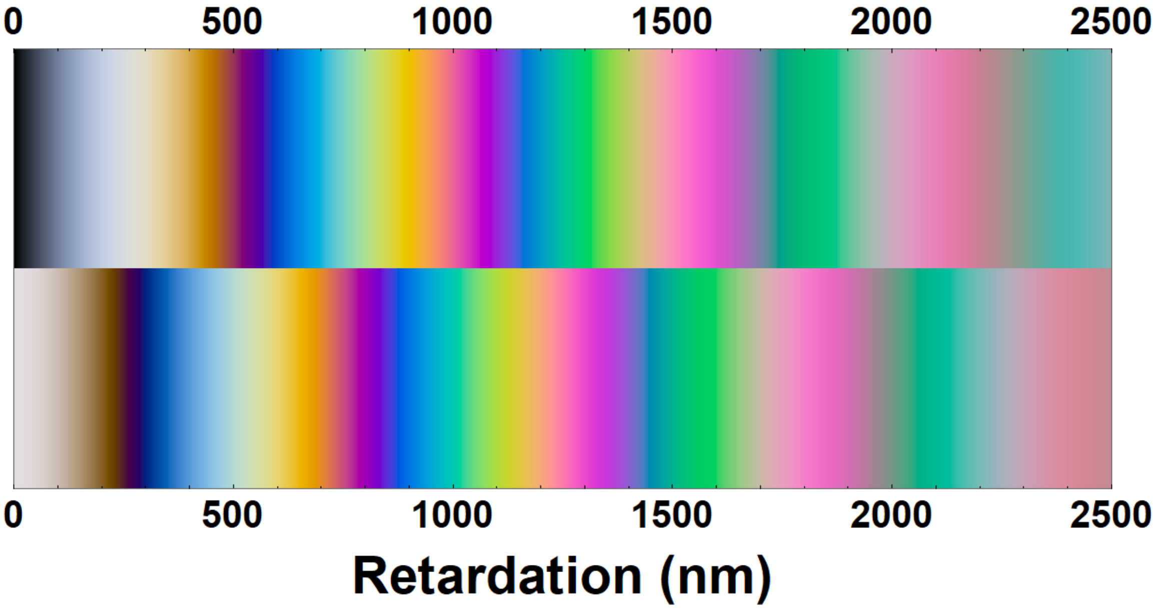


Fig. 4 Double slit interference pattern

Please look at the interference and diffraction patterns formed by other sets of double slits and see if the changes in slit spacing produce the expected changes in the patterns. You don’t need to make measurements. Please simply make qualitative observations, especially on how the space between the fringes change as the slit spacing is increased.

Now please ask the instructor to replace the red laser into a green laser. What kind of change do you expect to see in the interference and diffraction patterns? As you know the red He-Ne laser has a wavelength of 633 nm. Please estimate the wavelength of the green laser, based on the interference and diffraction patterns you have observed.



Calculated interference colors. The upper is for crossed polarizers and thin films. The lower is for parallel polarizers.

7. Michelson Interferometer

In this lab we are going to observe the interference patterns produced by two spherical waves and by two plane waves. We will study the operation of a Michelson interferometer, and use this interferometer to measure the laser wavelength and the refractive indices of some materials.

1) Glass plate fringes [Room 312]

You can create interference fringes by reflecting a laser beam from a glass plate. Each surface of the plate reflects the beam and forms a virtual image. The two images, which are coherent, create a two-source interference pattern. The fringes are real and can be formed on a screen.

Let us first observe the interference patterns between two *spherical waves*, which are circular fringes. As shown in Fig.1, please place the 18 mm positive lens on an element holder and position the lens close to the laser. Place the glass plate on a second element holder and position it in the middle of the optical bench. Place a white card (or a piece of white paper) with a small hole in it on a third element holder. Place the element holder as close as possible to the laser focus such that the laser beam passes through the hole on the card freely.

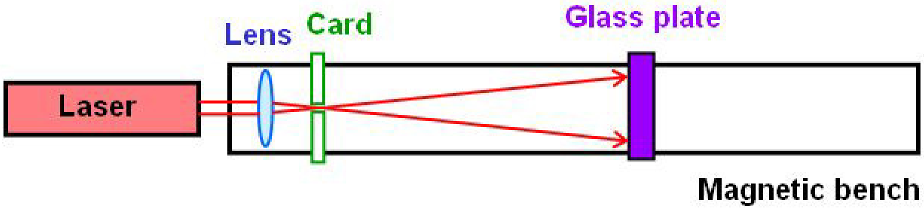


Fig.1 Observing the interference pattern from two spherical waves

The lens expands the beam so that the waves striking the glass plate are spherical. The waves reflected from the front and back surfaces of the plate create two coherent sets of spherical waves traveling back towards the laser. When these waves strike the white card, they interfere with each other and form a circular (bullseye) interference pattern, as shown in Fig.2. The pattern does not need to be centered on the hole. Note that you can see only a small portion of the total pattern at one time. If you rotate the glass plate you will see that you can scan the entire pattern. Can you find the center of the pattern? How does the pattern change when you move the glass plate left and right perpendicular to the axis of the optical bench? Explain the changes. How does the pattern change when the glass plate is moved closer to the screen? Explain the changes. Please take a photo of the interference pattern you have seen.

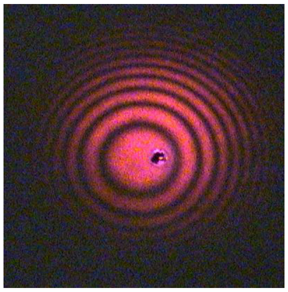


Fig. 2 Spherical-wave interference pattern

Now let us try to observe interference patterns from two *plane waves*. Please use the 252 mm lens in conjunction with the 18 mm lens to construct a laser beam expander (collimator). Adjust the separation distances until the beam is collimated. Place the glass plate near the end of the bench, as shown in Fig. 3. The waves reflected from the plate are now nearly coherent plane waves.

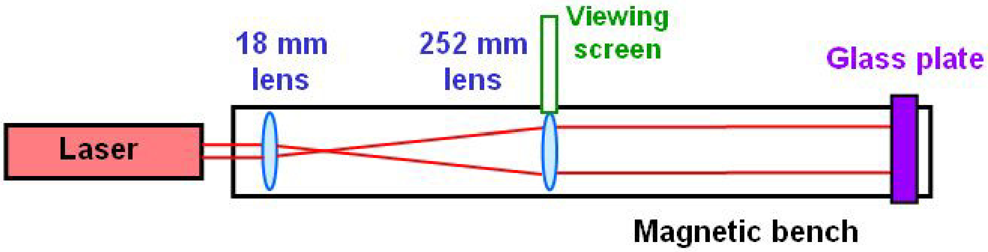


Fig.3 Observing the interference pattern from two plane waves

Place a viewing screen close to the 252 mm lens. You can do so by sticking a piece of white paper on the back of the element holder for the lens. When the reflected waves strike the viewing screen they form a plane-wave interference pattern, as shown in Fig. 4 (the fringes do not necessarily need to be vertical). You may need to slightly tilt the glass plate so that the fringes do not overlap with the incident laser beam. Please scan over the pattern by changing the orientation of the plate and convince yourself that it is a plane-wave interference pattern. How do you know that this is a plane-wave interference pattern? What happens to the fringe if you turn the glass plate around the laser beam by 90°? Please take a photo of the fringes.

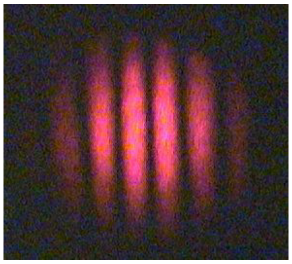


Fig. 4 Plane-wave interference pattern

2) PASCO Michelson interferometer [Room 312]

This part of the lab will be performed using the PASCO Scientific Company's *Complete Interferometer System*.

a) Set up the Michelson interferometer

A schematic of the Michelson interferometer is shown in Fig. 5. There are two angle brackets with mirrors mounted in them. The larger bracket and mirror is the beam splitter and the smaller one is the movable mirror. First please *remove* the 18 mm lens, if it is there. Swing the beam splitter out of the way of the laser beam. Adjust the X-Y position of the laser until the beam reflected from the movable mirror roughly (but not exactly) re-enters the laser. Now position a viewing screen (a white screen with a millimeter scale) on an element holder and set the assembly to the *right* of the movable mirror. Observe the image of the laser beam on the viewing screen. Instead of using the viewing screen you can stick a white paper on the wall at the place where the laser beam hits the wall. There will probably be one main dot and several secondary dots. They are resulted from the multiple reflection and transmission from the movable mirror. Carefully adjust the laser position until there is only one image dot. The laser beam should now be perpendicular to the movable mirror.

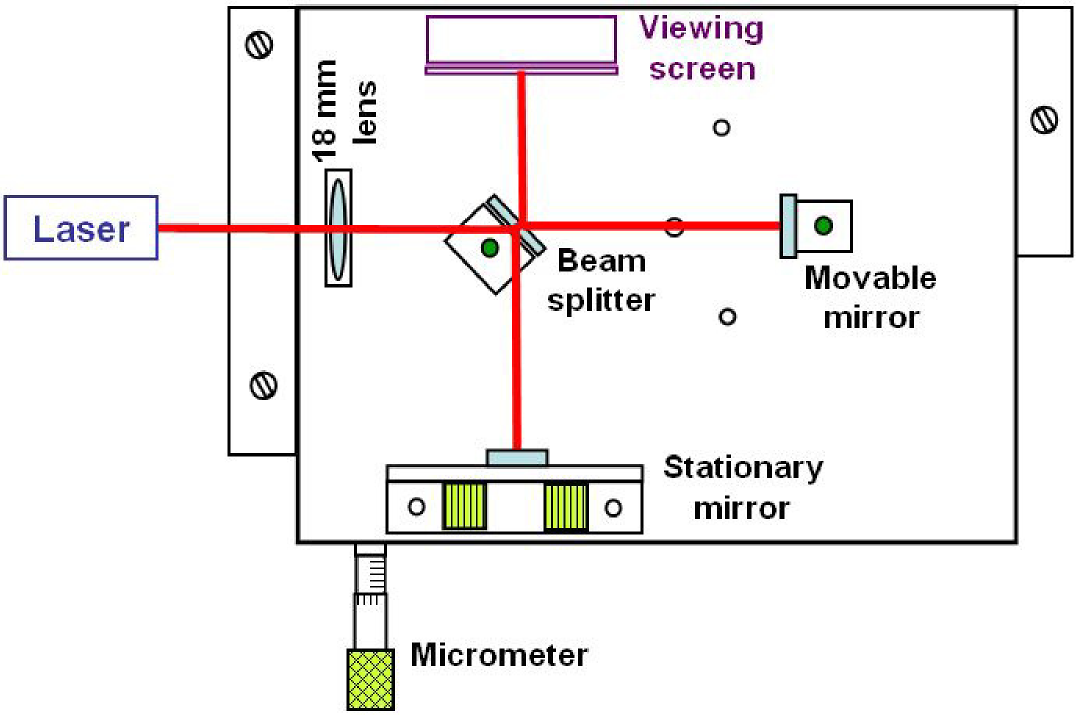


Fig. 5 Schematic of a Michelson interferometer

Swing the beam splitter back into the laser beam so that part of the beam is reflected to the stationary mirror. Adjust the position until the reflected beam hits the stationary mirror near its center. Now set the viewing screen assembly on the rear edge of the interferometer base as shown in the figure above. Instead of using a viewing screen you can also stick a piece of white paper on the wall. There should be two sets of bright dots on the screen. They are the reflections from the movable mirror and the stationary mirror. Now finely adjust the beam splitter again until the two sets of dots are as close together as possible. Secure the beam splitter via the thumb screw. Using the two adjusting knobs on the back of the stationary mirror, adjust the tilt of this mirror until the two sets of dots coincide. If you observe carefully you will see that when the two small dots overlap with each other they appear to split into segments separated by one or more dark lines. Please explain this phenomenon.

Now place the 18 mm focal length lens in front of the laser, or on the left edge of the interferometer base as shown in the figure above. Adjust the position of the lens very carefully until the diverging beam centers on the beam splitter. The setup should now resemble Fig. 5. You should see circular fringes on the viewing screen, as shown in Fig. 6. If not, very carefully adjust the tilts of the stationary mirror until the fringes appear. Once the fringes appear, center them using the fine adjustments of the stationary mirror. Please ask the instructor to have a look when you reach this point. If the laser is too strong you can use polarizers to reduce the light so that the fringes look better. Please take a photo of the fringes.

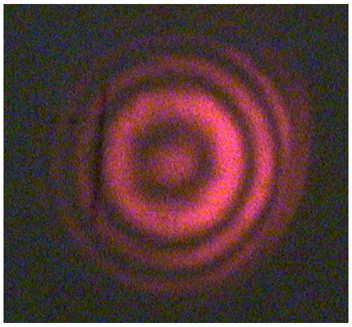


Fig. 6 Interference fringes from spherical waves

Please block either one of the light beams in the Michelson interferometer and see if the fringes are still there. Please slightly knock or press at the table and see what happens to the fringes. Please explain what you have observed.

Our measurement requires the counting of the number of the shifted fringes. Here is a small technique on how to do so. You can view the fringes on the viewing screen or on the paper on the wall. Move the micrometer dial and watch the fringes pass by. Use a pencil and draw a vertical (or horizontal) line on the screen paper as shown in the figure above. Use your judgment and line up the line to the boundary between one of the maxima and one of the minima by slightly adjusting the micrometer scale. Move the micrometer dial until the boundary between the next maximum and minimum reaches the same position as the original boundary. Now one fringe has passed by, and the fringe pattern should in principle look almost identical to the original pattern.

Turning the micrometer dial in (clockwise) moves the movable mirror toward the right. Turning the dial counter-clockwise moves the mirror toward the left. When turning the dial to count fringes, turn it one complete revolution in the direction you wish before counting fringes. This eliminates almost all possibility of *backlash*. Always take several readings and average them for better accuracy. The slip ring at the base of the micrometer adjusts the tension in the dial. When the ring is fully tightened, the dial will not move.

With a little practice you may be able to count the number of fringes with an accuracy of about 0.5 or 0.25 fringe, instead of one fringe.

For each of the following part of b), c) and d), please do the measurement *three times* and take the average as your final result.

b) Measure the wavelength of the laser

To measure the wavelength of the light used, simply count off about 30 fringes and record the distance the micrometer dial moved. One division of movement on the micrometer dial represents one micron of mirror movement (i.e. one revolution of the dial represents 25 microns of mirror movement). You should be able to read up to 0.1 micron precision on the micrometer. You should turn the micrometer very slowly and be careful in counting the number of fringes, so that you do not overlook or add one fringe. If the mirror moves a distance d, the optical path has changed by $2d$ since the light travels to and back from the mirror. Hence, the wavelength of light is obtained by dividing $2d$ by the number of fringes m:

$$\lambda = 2d/m. \tag{1}$$

c) Measure the refractive index of a glass plate

Now please set up the small rotating table. The bearing under the rotating table fits in the hole between the beam splitter and the movable mirror. It is held in place magnetically. Position the table so that the right hand edge of the lever arm is lined up with the zero on the degree scale on the interferometer base. Next mount the glass plate on an element holder and set it on the rotating table so that it is approximately perpendicular to the optical path. I believe the plate is made of BK7 glass. The thickness of the plate is marked on the holder. Please see Fig. 7 for the setup.

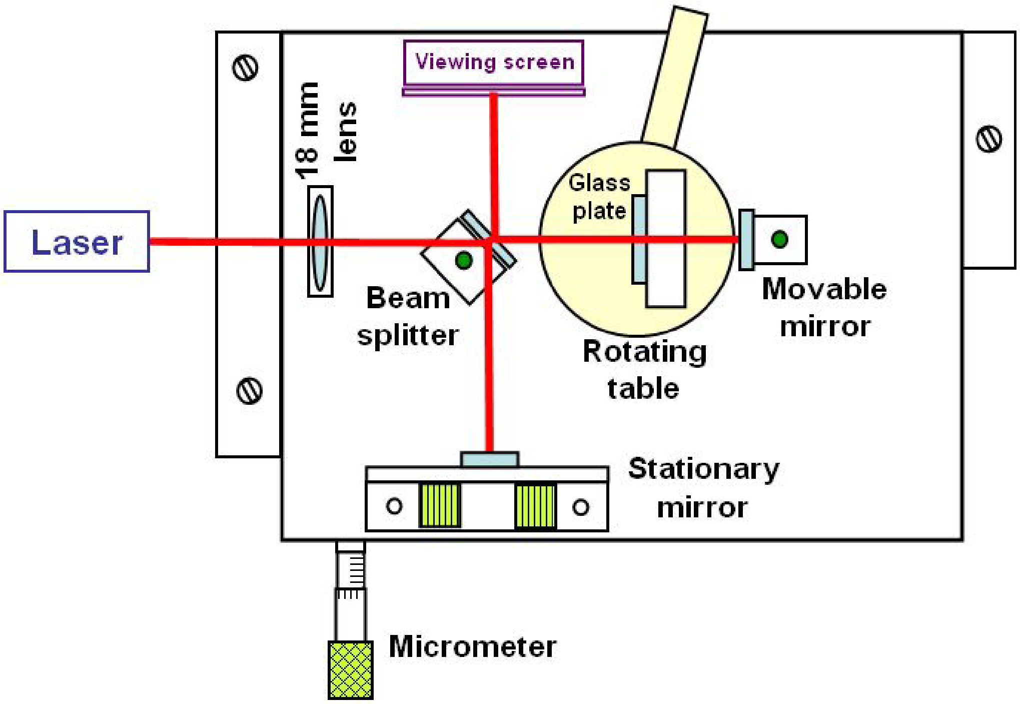


Fig. 7 Measuring the refractive index of a glass plate

Please make minor adjustments to get a clear set of fringes on the viewing screen. Please confirm that the level arm of the table is at the 0° mark. The validity of the equation that we are going to use to calculate the refractive index of the glass plate requires that the plate is initially exactly perpendicular to the light beams. This is achieved by the following method. First please finely rotate the plate by its holder (instead of the level arm of the table), and you will see that the fringe rings spit or swallow. Then please try to place the plate at the symmetric angle where the fringe rings will both spit (or swallow) after either a small clockwise or a small counterclockwise rotation. The plate is now exactly perpendicular to the laser beam.

Now carefully rotate the table by moving the lever arm. Watch the fringes go by. Count the number of fringes that pass by when moving the table from 0º to 10º. The light travels through more glass when the plate is sitting at 10º than when the plate is at 0º. Let t be the thickness of the plate, λ be the wavelength of the light, m be the number of the fringe shift, and θ be the angle that the plate has rotated. The index of refraction n of the plate is given by

$$n = 1 + \frac{m\lambda\cos\theta}{2t(1-\cos\theta) - m\lambda}\,. \tag{2}$$

d) Measure the refractive index of the air

Please remove the glass plate and the small rotating table used in the above section. Please position the gas cell between the beam splitter and the movable mirror. A picture of the setup is in fig. 8. The light beam should pass through the cell. Please make any minor adjustments to obtain a clear set of fringes. Because of the quality of the glass plates used in sealing the gas cell, the fringes may not be perfectly circular. This does not hurt because all we care about are how many fringes have shifted in the measurement. If the fringes are two thick (which means that the two images of the point light source are close), you can add a glass plate with similar thickness as the cell windows into the other arm of the interferometer. Now pump the air out of the cell. The fringes will fly quickly when you are pumping. When you stop pumping, the air will slowly leak into the cell, and the fringes will slowly pass by. Please first pump out the cell to a convenient pressure, then stop pumping and be ready to start counting the fringes. Note the initial reading of the gauge when you start counting, and the final reading of the gauge when you stop counting. A good suggestion is to count the shift of the fringes when the pressure is changing from about 500 torr (below one atmosphere) to about 100 torr.

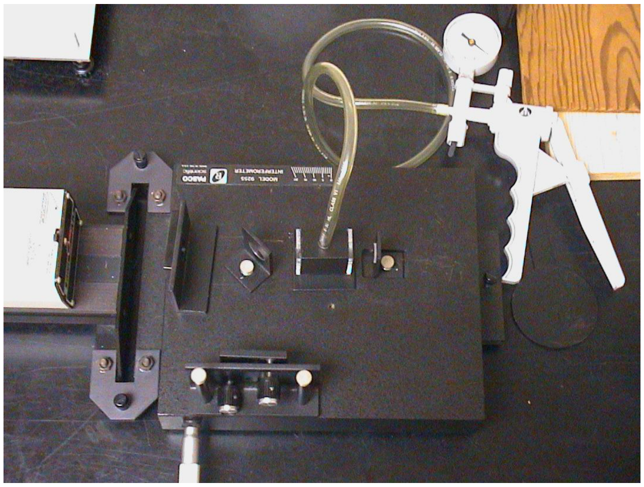


Fig. 8 Measuring the refractive index of the air

The refractive index of a gas varies directly with its density, and the index of vacuum is 1. Let d be the length of the gas cell (d =38 mm in our case), λ be the wavelength, m be the number of fringes, and P_i and P_f be the initial and final pressures of the air inside the cell. The refractive index of the air at 1 atmosphere is given by

$$n = 1 + \frac{m\lambda}{2d}\frac{1\,\mathrm{atm}}{\left|P_f - P_i\right|}. \tag{3}$$

In your lab report, for part b), c) and d), please derive Equations 1 and 3. Derivation of Equation 2 is optional. However, if you succeed you will be highly praised by Dr. Wang. It may take hours, if not days, to complete this task. Up to now Ben Chuang, one of my former graduate students, is the only student who has successfully derived this equation. Please show all your measured values and calculations. For part b) and d), please compare your experimental results with accepted values from other sources.

8. Holography

The purpose of this lab is to learn the basic principles of holography, and to make an actual hologram in our lab. This lab is full of fun. There is not much mathematics involved, so you do not need to do a lot of calculation. There is even not much work to do in the lab, except watching and thinking. The great thinker Blaise Pascal once said, "tout le malheur des hommes vient d'une seule chose, qui est de ne savoir pas demeurer en repos dans une chamber" (all men's miseries derive from not being able to sit in a quiet room alone). The ability to think deeply eliminates all men's misfortunes, and women's as well. Nevertheless, to understand the creation and application of holograms, you do need to have substantial background knowledge in light interference and diffraction. Also please note this lab has a nature criterion for evaluating your performance and my teaching, which is how clear and vivid your holographic image appears in our own eyes.

There may be one issue, which has never actually happened in the lab, but is possible to happen, that one or more holographic films may have degraded due to aging or manufacture defect. Each year I test one film some days before the lab, and make sure that it works well, but still we cannot guarantee the rest of the films will work. In such case, we will ask our department to order new films, and we will have to do the lab again in another day.

1. Principles of holography

Holography is the study of holograms. A *hologram* is a film that records the interference pattern produced by a reference light wave and an object light wave. The wonder of a hologram comes from the fact that even when the object is removed, the scattering of the reference light by the hologram alone will reproduce the three-dimensional image of the object. Holography thus includes two main steps: to *record* a hologram of an object, and to *reconstruct* the image of the object.

A hologram is different from a normal photograph in the way that the image it produces is three-dimensional, preserving original *parallaxes* and *depths* of the scene. That is, when you change your angle of view on a hologram, you see different relative positions of the objects, and you perceive the different distances of the objects from you. In addition, a normal photograph records a two-dimensional image of the object, while a hologram records an interference pattern. Furthermore, a normal photograph can be viewed under any light source, while viewing a holographic image usually requires the original light source used in recording the hologram, or a light source closely resembles the original light source.

1.1 Complex representation of a wave

To understand how holography works, we start from some mathematical description of light waves. In holography almost exclusively a *monochromatic coherent light source* is used, which means that the light has a single wavelength, and the phase difference of the wave between any two points in space does not vary with time. In holography, usually a laser is used as the light source, which has a very narrow bandwidth and a long coherence length. As a result, the light field E as a function of position vector $\mathbf{r}$ and time t can be written as

$$E(\mathbf{r},t) = A(\mathbf{r})\cos[\omega t + \varphi(\mathbf{r})] = \mathrm{Re}[A(\mathbf{r})e^{i[\omega t+\varphi(\mathbf{r})]}] = \mathrm{Re}[A(\mathbf{r})e^{i\varphi(\mathbf{r})}e^{i\omega t}] = \mathrm{Re}[a(\mathbf{r})e^{i\omega t}] \tag{1}$$

Here $A(\mathbf{r})$ is the amplitude of the wave. It is a non-negative real number. For simplicity we assume all lights are linearly polarized in a certain direction. The letter ω denotes the angular frequency of the monochromatic wave. The function $\varphi(\mathbf{r})$ is the *phase* of the wave. The function $a(\mathbf{r})$, which is given by $a(\mathbf{r}) = A(\mathbf{r})e^{i\varphi(\mathbf{r})}$, is the *complex amplitude* of the wave. For the study of interference and diffraction, it is adequate to drop the Re[] symbol in Eq. (1) and simply write

$$E(\mathbf{r},t) = a(\mathbf{r})e^{i\omega t}\,. \tag{2}$$

Eq. (2) is called the *complex representation* of a wave. In this representation the light wave is fully described by its complex amplitude $a(\mathbf{r})$, with the understanding that the actual wave is given by its real part. The *intensity* of the light wave in space is then given by

$$I(\mathbf{r}) = |a(\mathbf{r})|^2 = a(\mathbf{r})a^*(\mathbf{r})\,. \tag{3}$$

When only one monochromatic light wave with a fixed frequency exists in space, it suffices to further drop the $e^{i\omega t}$ factor and use the complex amplitude $a(\mathbf{r})$ only to specify the light wave.

1.2 Record of a hologram

As we have known, a hologram is a record of an interference pattern. The principle of recording a hologram is shown in Fig. 1a. Suppose a laser beam is focused on a point R, which emits a nearly spherical *reference wave*. Suppose the laser beam has been split by some method, and a portion of light strikes on the object for which we want to make a hologram. Here the object is a solid little bunny, which emits an *object wave*. The hologram is recorded by a *holographic film*, which is located in the *xy* plane. Suppose on the holographic film the complex amplitude of the object wave is $o(x, y)$, and that of the reference wave is $r(x, y)$. In an actual setup the reference wave $r(x,y)$ is close to a plane wave, or a small portion of a spherical wave, which is called a *simple reference wave*. The magnitude $|r(x, y)|$ is therefore almost uniform across the surface of the film.

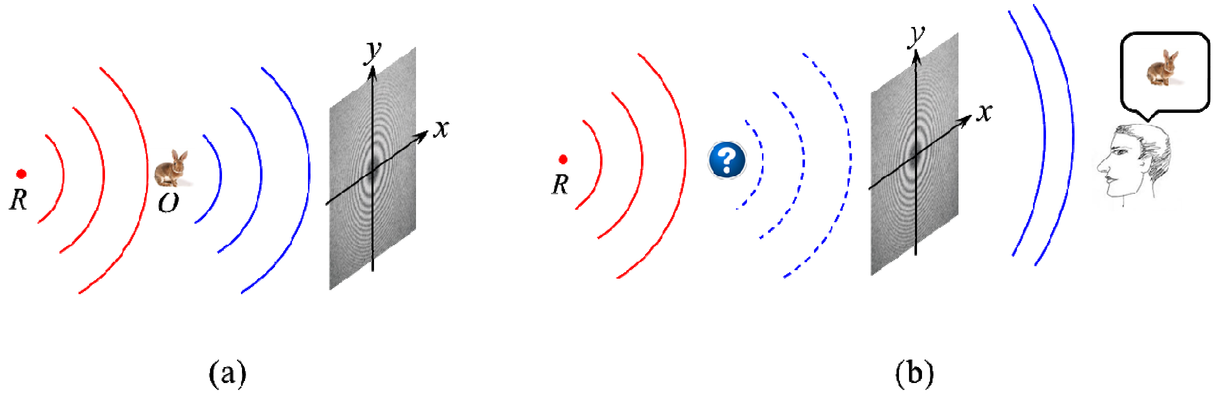


Fig.1 (a) Record of a hologram. (b) Reconstruction of the image.

The object wave $o(x, y)$ contains all information about the three-dimensional appearance of the object. To understand this we can decompose this complex wave back into a number of spherical wavelets originating from different points on the bunny with different source strengths, say some from the eyes, and some from the mouth. When these spherical waves hit our eyes, they will be focused on our retina to create a picture, which our brain interprets as an image of the bunny. When we change the angle of view, the image on our retina, resulting from $o(x, y)$, will also change, so that our brain interprets the image as being three-dimensional. Therefore, the object wave $o(x, y)$ contains everything we need for the three-dimensional image of the object. In addition, the theory of diffraction states that if we know the object wave $o(x, y)$ at any surface, here the *xy* plane, we can calculate its complex amplitude at any subsequent or previous surfaces. That is, in optics, a two-dimensional wave distribution in a surface uniquely determines the three-dimensional light field distribution beyond the surface, if there are no additional sources. This is no more than a restatement of the Huygens-Fresnel principle. Therefore, in order to record a three-dimensional image of the object, we only need to record the amplitude and phase of the complex object wave at a certain two-dimensional plane in space. The essence of holography lies on how to record and how to reconstruct the object wave.

Now the total light field on the holographic film plane is $r(x, y) + o(x, y)$, and its intensity is

$$I(x, y) = |r(x, y) + o(x, y)|^2 = |r(x, y)|^2 + |o(x, y)|^2 + r^*(x, y)o(x, y) + r(x, y)o^*(x, y)\,. \quad (4)$$

This light intensity is a measurable, and it contains both the amplitude and the phase information of the object wave. Roughly speaking, at a small area on the hologram the contrast of the fringes indicates the amplitude of the local object wave, and the position of the fringe indicates its phase. When the holographic film is exposed to the light field for some time and then developed, its optical property, here the transmittance or reflectance, will change due to the existence of the fringe pattern on it. Any currently used optically sensitive material responds only to the intensity of the light. We now *assume* that after *development* the *amplitude transmittance* (also called the *amplitude transmission coefficient*) of the film, which is the ratio between the amplitude of the transmitted light and that of the incident light, is a *linear* function of the light intensity on the film plane that was used to expose the film. That is

$$t(x, y) = t_0 + \beta I(x, y)\,. \quad (5)$$

Here t_0 is a constant background transmittance, and β is a parameter that is determined by the material and size of the holographic film, as well as by the experimental condition. Both t_0 and β are constants, but may be complex. We will soon discover that the requirement that the amplitude transmittance be linear to the exposing light intensity, i.e., Eq. 5, is essential for reconstructing a good image of the object. A recorded hologram is uniquely specified by its amplitude transmittance Eq. 5, where the light intensity pattern $I(x, y)$ is given by Eq. 4.

We can now safely say that sufficient information on the object wave $o(x, y)$, or the three-dimensional image of the object, has been stored inside the hologram in the form of special fringe patterns $I(x, y)$. Unless you are an extremely intelligent genius, you are not supposed to realize the image in your brain simply by examining the fringes on the hologram. This is in analogy to the music tracks on a CD. We know that everything is well recorded there, but it is practically impossible for us to figure out what music it exactly is by simply analyzing the surface of the CD without the help of a computer or a CD player.

1.3 Reconstruction of the image

We now remove the object and develop the film following a certain procedure. We then reconstruct the image by shining on the film using a light wave that has the same wavelength, same source location and same propagation direction as the reference wave that has been used in recording the hologram, as shown in Fig. 1b. The light field incident on the hologram plane is given by $r(x, y)$, apart from a possible constant factor which scales the overall light intensity. The hologram has a transmittance given by Eq. 5. Therefore the complex amplitude of the light field transmitted from the hologram is

$$\begin{aligned} f(x,y) &= r(x,y)\; t(x,y) \\ &= r(x,y)\left\{ t_0 + \beta\left[|r(x,y)|^2 + |o(x,y)|^2 + r^*(x,y)o(x,y) + r(x,y)o^*(x,y) \right] \right\} \\ &= \left[t_0 + \beta |r(x,y)|^2 \right] r(x,y) + \beta |o(x,y)|^2 r(x,y) + \beta |r(x,y)|^2 o(x,y) + \beta r^2(x,y)\; o^*(x,y) \end{aligned} \tag{6}$$

Recall that for a simple reference wave its magnitude $|r(x, y)|$ is almost constant across the holographic film surface. The first term in the transmitted wave, $\left[t_0 + \beta |r(x,y)|^2 \right] r(x,y)$, is the attenuated reference wave. The second term, $\beta |o(x,y)|^2 r(x,y)$, is close to the form of the reference wave. It produces a *halo* around the reference wave, whose angular spread is determined by the unevenness of the intensity of the object wave on the hologram plane, i.e., $|o(x,y)|^2$. Usually the object wave is made less intense than the reference wave, so this term is small compared to all other terms. The third term, $\beta |r(x,y)|^2 o(x,y)$, is of our most interest. It is identical to the object wave $o(x,y)$ up to an amplitude constant. It produces a virtual three-dimensional image of the object, here the little bunny, at its original position when the hologram was recorded. Our eyes cannot distinguish this wave from the original object wave by any optical method. This is exactly the wonder of a hologram. Please note the condition that the amplitude transmittance be linear to the light intensity used in film exposure, i.e., Eq. 5, is an important requirement to bring this miracle to occur. The fourth term, $\beta\, r^2(x,y) o^*(x,y)$ has an opposite wavefront curvature compared to the object wave. It therefore produces a *conjugate image*, which is a real but mirrored image of the object. The conjugate image may be deflected from the main axis by the phase of the $r^2(x,y)$ factor.

You may wonder now if we shine the hologram with only the object wave, then perhaps the reference wave will be reproduced. In principle if two waves with arbitrary shapes interfere and produce a hologram, then shining the hologram with either one of the two waves will reconstruct the other, and its conjugate wave as well. However, referring to the term $\beta |r(x,y)|^2 o(x,y)$ in Eq. 6, in order to reconstruct a wave (here $o(x,y)$) with good quality, the other wave (here $r(x,y)$) must have a nearly uniform intensity across the hologram plane. Therefore, a simple reference wave is important in recording and reconstructing a hologram.

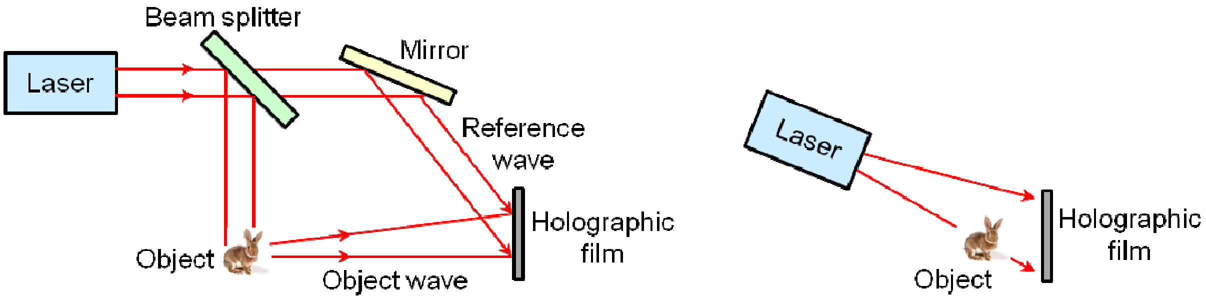
For simplicity in Fig. 1 the reference wave and the object wave are shown to be collinear. This is called *on-axis holography*. In on-axis holography the reconstructed virtual image is in-line with the reference wave, the halo and the conjugate image. The image thus does not have a high quality. In practical holography, the directions of the reference wave and the object wave are sufficiently offset from each other, so that the virtual image is well separated from the reference wave, the halo and the conjugate image in space. This is called *off-axis holography*, for which we will have many examples in the following sections.

2. Transmission holograms and reflection holograms

There are several different ways to categorize holograms, each indicating certain physical properties of the holograms as well as certain techniques needed in recording them. Depending on whether the holograms modify the amplitude or the phase of the incident light wave, they are classified as *amplitude modulation holograms* or *phase modulation holograms*. Depending on whether the thickness of the holograms is less or more than the separation between the interference fringes, which is usually on the order of a wavelength of the light source, they are classified as *thin holograms* or *volume holograms*. Depending on whether the laser light is transmitted or reflected from the holograms to reconstruct the image of the object, they are classified as *transmission holograms* or *reflection holograms*. Here we will detail on this classification because it is necessary in understanding the geometric arrangement of the laser, the object and the holographic film in our experiment.

2.1 Transmission holograms

In a transmission hologram, the reference wave and the object wave incident on the holographic film from the same side. Fig. 2a shows the top view of a typical setup for recording a transmission hologram. The laser beam is split by a beam splitter. One branch of the light beam from the beam splitter, here the transmitted light, is reflected by a mirror and then shines on the holographic film. This light beam is close to a plane wave and serves as the reference wave. The other branch of the light from the beam splitter strikes on the object, from which the scattered light servers as the object wave. The setup in Fig. 2a is actually an *amplitude-splitting interferometer*. A much simplified version of the setup for recording a transmission hologram is shown in Fig. 2b, which is a *wavefront-splitting interferometer*. Here the laser light is close to a spherical wave, and the object is placed only in one part of the laser beam. The interference fringes are produced by the light that directly shine on the film, which is the reference wave, and that has been scattered from the object, which is the object wave.



(a)

(b)

Fig.2 Typical setup for recording a transmission hologram (a), and a simplified setup for recording a transmission hologram (b).

In general, when two light beams interfere the resultant fringes in space are planes that bisect the two beam directions. Therefore, on a transmission hologram the fringes are in the film plane, like the grooves on a grating, or the fingerprints on your fingers. This structure usually prevents a transmission hologram from being viewed using a white light source. Due to the effect of chromatic aberration, the images of different colors are continuously spread into different directions, in a similar way like a grating diffracting white light into various directions.

To reconstruct the image of the object from a transmission hologram, we just remove the object and look from the other side of the developed hologram. A virtual three-dimensional image appears at the original position of the object. Because the light source transmits through the hologram to produce the image, hence comes the name transmission hologram.

2.2 Reflection holograms

In a reflection hologram, the reference wave and the object wave are incident on the holographic film from the opposite sides. Fig. 3a shows a typical setup for recording a reflection hologram. Please note compared to Fig. 2a here the reference wave strikes on the film from the other side. A much simplified version of the setup for recording a reflection hologram is shown in Fig. 3b. Here the laser beam is close to a spherical wave. The light beam first strikes on the front surface of the film, which serves as the reference wave. Part of the light beam transmits through the film, which strikes on the object and is then scattered back onto the rear side of the film. The light scattered from the object serves as the object wave.

Since in a reflection hologram the reference wave and the object wave propagate in somehow opposite directions, they form partially standing waves in the holographic film. The fringe planes are layers nearly parallel to the surface of the film, like the pages in a book. This makes the hologram effectively behave like an interference filter.

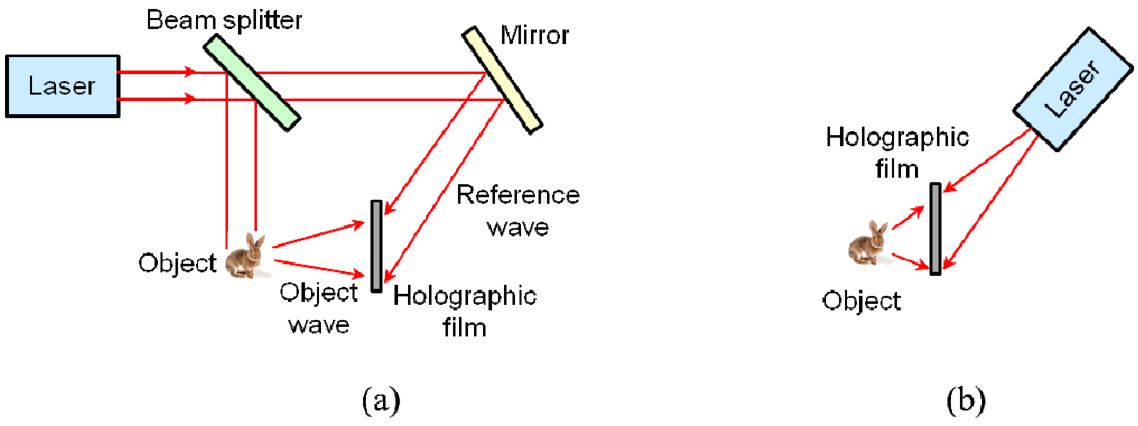


Fig. 3 Typical setup for recording a reflection hologram (a), and a simplified setup for recording a reflection hologram (b).

To reconstruct the image of the object from a reflection hologram, we just remove the object and look from the other side of the developed hologram. Because the image is formed through the reflection of light from the film, necessarily the hologram should be a volume hologram since a thin layer generally has a very low reflectance. The multi-layer structure of the fringe planes provides us with a significant advantage. That is, the image can also be viewed using a white light source. This is because the light that has a wavelength of the original laser will have an enhanced reflectance compared to all other wavelengths, much like the multi-layer coating on a glass. However, please do not expect the image is as clear as what you see using a laser light source. This is because a white light source has a short coherence length, even if it has been filtered into a monochromatic light. In addition, the remaining chromatic aberration due to the finite transmission bandwidth of the hologram will also blur the image.

3. Experimental apparatus

In this lab we are going to record a reflection hologram using the simplified setup scheme as shown in Fig. 3b. The apparatus is a modified hologram kit from Litiholo. The kit is modified into a solid construction using some opto-mechanical elements from Thorlabs. The most advantage of this kit is that their holographic film is “instant” and develops itself simultaneously in the course of exposure. Therefore, there is no need to develop the films after the exposure. The image can be directly seen by just removing the object. This will save much of our time and allow us to concentrate on the physics of holography itself. I do not mean that developing films has no fun. Playing with chemical solutions involves much physics, and has much fun as well. The point is, the holographic films from Litiholo are not only instant, but also inexpensive, and are of sufficiently good quality at the same time. The specification sheet says that the film has a thickness of 16 μm. It is coated on a glass plate together with a 175 μm polycarbonate cover. The film plate has a surface size of 2"×3". The diode laser we currently use has a wavelength of 635 nm, and a power of about 7 mW. There is a small battery-power supply box, where we can choose to use either a 3V battery, or a 3V DC regulator to drive the laser diode. It is suggested that we use the DC regulator when recording the hologram, because many times the battery may be old, and the laser power is sensitive to it. The laser light is linearly polarized in the beam expansion direction. The focusing lens of the laser has been removed so that the light beam diverges in space quickly, which produces a large spot with an elliptical shape. The films we currently use are only sensitive to red light and need about 20 mJ/cm^2 exposure energy at the wavelength of our laser.

Our apparatus for recording a reflection hologram is shown in Fig. 4. The film plate (here actually a blank glass plate) and the object (here a ceramic dog) are enlarged and shown in Fig. 5. As shown in Fig. 4, all mechanical, optical and electronic items are mounted on a 8"×8" breadboard, which makes the whole device compact and portable. The diode laser is fixed on a horizontal cylindrical bar on the top. As shown in Fig. 5, the film plate sits in a slot on the plate holder, and leans on one side against a plastic plate support. This ensures that the film plate does not move in the course of recording the hologram.

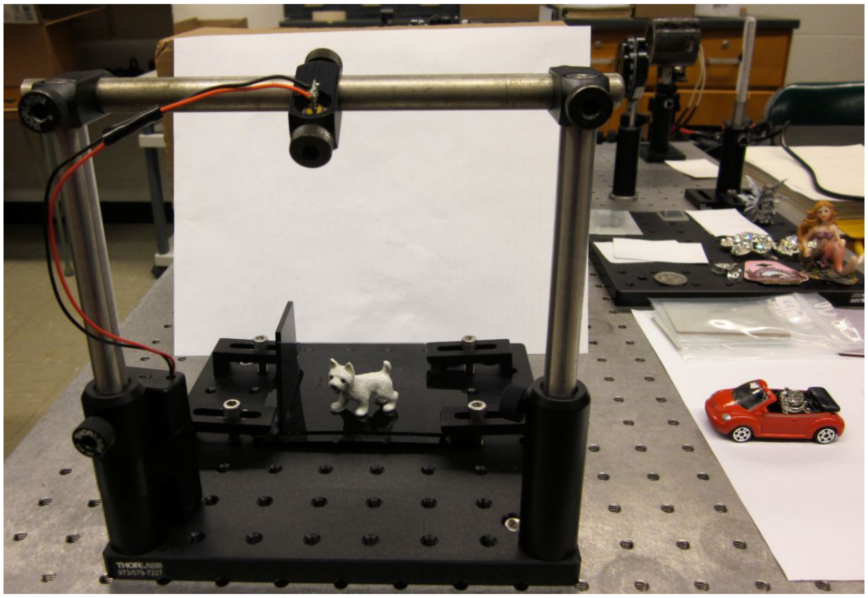


Fig. 4 Experimental apparatus for recording a reflection hologram.

Fig. 5 Blank film plate and the object (a ceramic dog).

You have three options in choosing the objects. They are the lovely ceramic dog and a deer, the ceramic fish and a crab, or a red miniature car carrying a sparkling earring of a dolphin. Some of them can be seen in Fig. 4. The car came originally from Litiholo. Many of the other trinkets and jewelries were bought by me at the Old Fisherman's Wharf in Monterey, California, where currently each year in the summer my children and I have to spend some time. California coasts are like a desert. I like Macomb more. Macomb is the best place in this world to do physics; however, it is unfortunate that God does not let you know this truth until you get older.

4. Experiment

Please check that the breadboard is firmly fixed on the optical table. Please check that the laser holder, the plate holder, and the plate support are rigid. Please place the blank film plate in the slot of the plate holder and let it rest freely on the plate support. Please check the position of the laser. Currently the laser is about 160 mm vertically from the base breadboard, and about 66 mm horizontally to the front edge of the plate holder.

Please turn on the laser diode. The laser needs to have a warm-up time of at least 5 minutes before recording a hologram. Please use a white paper card and verify that the expanded laser beam is properly passing through the center of the blank film plate. If needed, the laser can be rotated around or slid along the horizontal bar after loosening its setscrews. Please measure the power of the laser beam using a laser power-meter. It should be about 7 mW. If necessary, we can change the batteries for the laser.

Please place the object behind the blank film plate as close as possible, but without touching the plate. This can be confirmed by looking at the mirror image of the object from the back side of the plate, and make sure that there is about 1 mm distance between the most tip of the object and its image in the plate. Please confirm that the object is mostly illuminated by the laser beam that has passed through the blank film plate.

Please now look at the object from the laser side through the blank film plate. What you see now is what you see later for the reconstructed image. Therefore please spend some time and finely adjust the position and orientation of the object. Rotate it slightly if necessary. Place a coin beneath the object or a mirror behind the object for additional illumination if it is dark there. Finally please confirm again that the object is close to the blank film plate, but does not touch the plate.

The whole hologram recording takes about 10-15 minutes. ABSOLUTE SILENCE is important in this period. Recall that a motion of only a quarter of a wavelength, which is about 150 nm, or 1/300 of the diameter of a human hair, of the object (similarly the film plate or the laser) may switch the bright and dark fringes in the film and wash out all information. You can choose to stay either in the lab or outside of the lab in this period. If you choose to stay outside, please do not knock at the door, and wait until we call you in. If you choose to stay inside and watch the whole process of recording the hologram, please do the following:

1) Please use the bathrooms now if needed.
2) Please keep a distance of at least a foot from the table.
3) Please shut off or mute your cell phones.
4) Please put your notebooks, your pencils and your bags in a far and safe place.

5) Please orally *promise* me that you do not talk, do not breathe to the hologram, do not touch the table, do not walk, do not write, do not use your cell phones, and do not flip book pages in this period.
6) It is recommended that you use this time to only watch at the hologram film and think about whatever you normally do not have time to think.

Please put a large sign of "Holography lab. Do not disturb." on each door of the lab, and close the doors. Please place a black paper or board between the laser and the blank film plate and totally block the light on the plate. Please turn on the blue LED light, which is for use as a flashlight in the dark room. Recall that our film only responds to red light. Please turn off all ceiling light, and any other light in the lab. Please confirm that we are now in the darkness. Please open the film box and take out only one film plate, and then seal the box. Please confirm that you actually sealed the film box, otherwise we may risk ruining all the films left in it. Please remove the blank film plate and replace it with the real film plate. It is suggested that the plastic cover of the holographic film face the laser source. This is because the plastic cover is found to be somehow birefringent. It may change the polarization of the reflected light if it faces the object, which may reduce the contrast of the interference fringes. The thin holographic film itself and the glass plate have no remarkable birefringence.

Please wait 3-5 minutes to let everything become quiet down. Please remind yourself again that we need absolute silence, and you are supposed to *only watch and think* in this period. Now please gently remove the black paper and let the laser shine on the film plate. This starts the recording of the hologram. The total exposure time is 10-15 minutes. You may watch through the film plate and notice some interesting changes of the appearance of the object in this period, but please do not talk. Please remember it in your mind and ask questions only after we have finished recording the hologram.

The instructor will announce the completion of the recording of the hologram. We can now switch a lamp and some ceiling lights on. Please keep the area a little dark for viewing the hologram most effectively. Please call in the persons who have chosen to stay outside. Please remove the sign on the lab door. Now please assign a person who is going to remove the object away while everybody is watching at the hologram. Please predict what will happen before removing the object. You should be successful because you have worked so hard. However, if you are not lucky this time, you can try one more film plate.

If needed you may finely adjust the laser height and direction until you see the brightest image. This is because during the exposure the holographic film may be minutely deformed a little by thermal or chemical effects. A slight change in the position of the light source may compensate the change in the film.

Please take several photographs of the holographic image of the object using your camera from a few different viewing angles. Please make sure that your photographs demonstrate that the hologram shows proper parallaxes and depths of the original scene.

You can also view the hologram under white light illumination. Please watch the hologram under a white light lamp, which shines on the hologram at an angle and distance similar to that of the laser beam. You may need to tip the hologram around so that you catch the brightest image. Please take a photograph that shows your hologram can be viewed under the white light lamp.

If it is sunny, please bring the hologram outside of the building and observe it there.

5. Additional questions (Optional)

1) As shown in Fig. 2a, a laser with wavelength λ is used to record a transmission hologram. The angle between the directions of the reference light beam and the object light beam is θ. The holographic film surface is placed to be roughly perpendicular to the bisector of the two beam directions. Please estimate the distance between the interference fringes on the hologram.

2) Suppose there is a plant growing at an extremely slow speed of about the thickness of a hair (about 0.045 mm) a day. The plant is small enough to fit in our setup, and is strong enough to resist any vibration. Can our apparatus make a hologram of the plant?

3) Suppose about 1/3 of the whole laser beam energy shines on our holographic film. Please estimate the exposure time needed in our experiment if an exposure energy of 20mJ/cm^2 is needed.

9. Polarization

In this lab we are going to study the various phenomena related to the polarization of light. We will also learn how to analyze, control and transfer the polarization state of light. This lab is by far the most interesting in this semester.

I am going to demonstrate most of today's experiments to the class. However, at some stage you will be asked to explore with your own minds and your own hands. Please make sure that you 1) take notes, 2) take photos, and 3) ask questions while you are observing my demonstration.

1) General observations [Room 310]

The plastic linear polarizer we currently use has a size of 4.5"×5", with its transmission axis parallel to its shorter side. Please handle the polarizers by their edges, and avoid scratching their surfaces.

i) Ceiling lights — Please hold a polarizer in one hand and look through it at one of the ceiling lights. Rotate the polarizer through 360º. What happens to the intensity of the transmitted light? What is the polarization state of the light emitted by the ceiling lights?

Please hold one polarizer in each hand, one in front of the other, and look through them at a ceiling light. Now rotate one of the polarizers through 360º while keeping the other intact. What happens to the intensity of the light being transmitted through the two polarizers? What is the angular relationship between the transmission axes of the two polarizers when the light is blocked? Explain your observations.

ii) Glare — Please find a place on the floor of the lab where you can see the "glare" (reflection) from the light bulb of a lamp. You may need to turn off the ceiling lights. Look at the glare through a single polarizer close to your eye and rotate the polarizer through 360º. At the minimum transmission, you can further reduce the transmitted light intensity by adjusting the angle of reflection. This is done by moving yourself a little bit forward or backward. What is the orientation of the transmission axis of the polarizer when the glare is minimized? What is the polarization direction of the light being reflected from the floor? Why are polarizers useful as sunglasses? Actually this provides the easiest method to determine the transmission axis of an unknown linear polarizer.

Please measure the Brewster angle for the light reflected from the floor. Include appropriate data and a sketch showing how you made the measurement.

iii) Polarization by scattering — Please put a flashlight above a full cylinder of water. An aperture with a diameter of about 5 mm is used to limit the size of the light beam. The setup is shown in Fig. 1. Let us observe the light scattered by the water molecules. We need to turn off all ceiling lights.

You can see the flashlight beam appearing as a post in the water. They are light scattered by water molecules and floating particles. Before you use a polarizer, discuss with your partners on what you will see when looking at the scattered light in the direction perpendicular to the flashlight beam through a polarizer. Now please hold a polarizer in front of your eyes and look toward the light at an angle of about 90º from the flashlight beam. Rotate the polarizer slowly and observe the change in intensity of the light being transmitted by the polarizer. What is the polarization direction of the scattered light from the water? Based on the oscillating dipole theory, explain briefly why the light is polarized like that.

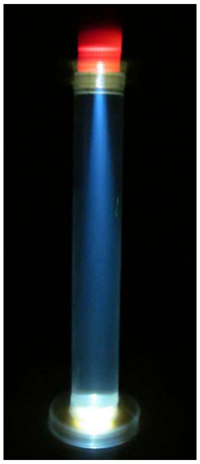


Fig. 1 Observing light scattered from water

iv) Directional dependence of dipole radiation — Now insert a polarizer between the flashlight and the aperture. Rotate the polarizer so that its transmission axis is perpendicular to the blackboard of the classroom. Look at the light beam in the water directly while going 360º around the water container. You should notice that there are two special directions in a line where the scattered light almost disappears, while their perpendicular directions have the strongest scattering. What is the relation between the direction that has the strongest scattering and the direction of the electric dipole of the water molecule? Explain what you have seen using the theory of directional dependence of dipole radiation.

2) Light transmission through polarizers [Room 312]

The transmission axis of each rotational polarizer is parallel to the line connecting the 0º and 180º marks. However, it can be a few degrees away due to the lack of care of the maker. Please don't touch the surfaces of the polarizers or the wave plates. Always handle them by their holders.

Please attach a polarizer to an optical element holder and position the holder on the optical bench so that the laser beam passes through the polarizer and then strikes on a viewing screen. Rotate the polarizer through 360º and observe the intensity of the transmitted beam. What do you conclude about the polarization of the laser — is it completely polarized, partially polarized, or randomly polarized?

Attach two polarizers onto two optical element holders and position the polarizers on the optical bench so that the laser beam passes through both of them and then strikes on the viewing screen. Adjust the first polarizer (the one closer to the laser) so that the 0º mark of the polarizer lines up with the white mark on the bottom of the element holder. From this point on we let the *angle of a polarizer* be the degree mark that lines up with the white mark on the holder. Now rotate the second polarizer through 360º and observe the intensity of the transmitted beam. The intensity should go to zero when the angle of the second polarizer is at 90º relative to the first polarizer. For real world polarizers it will approach zero but never be exactly equal to zero. When the two polarizers are at right angles to each other, they are said to be *crossed*. The transmitted beam is said to be *extinguished* when its intensity approaches zero.

The second polarizer in the above measurement can be thought of as a "polarization analyzer". When a light beam can be extinguished by a linear analyzer, you can be sure that the beam is linearly polarized and that the polarization axis of the beam is perpendicular to the transmission axis of the analyzer at extinction.

Please make *qualitative* observation on the final transmitted light intensity as a function of the angle between the two polarizers, for angles of 0º, 10º, 20º, 30º, 40º, 50º, 60º, 70º, 80º and 90º. You may need to turn off the light when observing very weak lasers. Please see if your observations agree with Malus's Law.

Describe how you could use two polarizers to reduce the intensity of a laser to any desired value. What are the upper and lower limits on the intensity you can achieve (as a fraction of the initial intensity of the laser, supposed to be randomly polarized)?

Position the two polarizers so that they are crossed. No light should be transmitted. Now place a third polarizer between the other two. Rotate the third polarizer. What happens to the intensity of the transmitted beam? Please explain.

3) Reflectance [Room 312]

Please place the small rotating table on the bench and position the acrylic plate on the table so that the laser beam strikes the front face of the plate at an angle of incidence of

10º. Note that the plane of incidence of the laser beam is now horizontal. Position a polarizer between the laser and the plate and orient the polarizer so that its transmission axis is vertical. The laser light striking the plate is now polarized in a direction perpendicular to the plane of incidence, which is called *s*-polarization. Now adjust the plate position so that there is only one reflected beam. This can be done by striking the laser beam close to one edge of the plate. A picture of the setup is shown in Fig. 2.

Please make *qualitative* observation on the change of the intensity of the reflected light, when you change the angle of incidence to 20º, 30º, 40º, 50º, 60º, 70º and 80º, and as close as possible to 90º.

Repeat the above observation with the polarizer oriented so that its transmission axis is horizontal. The laser light will now be polarized parallel to the plane of incidence, which is a *p*-polarization. Please make *qualitative* observation on the change of the intensity of the reflected light when you change the angle of incidence. Especially please measure the value of the Brewster angle, which is the angle where the reflectance of the *p*-polarization drops to zero.

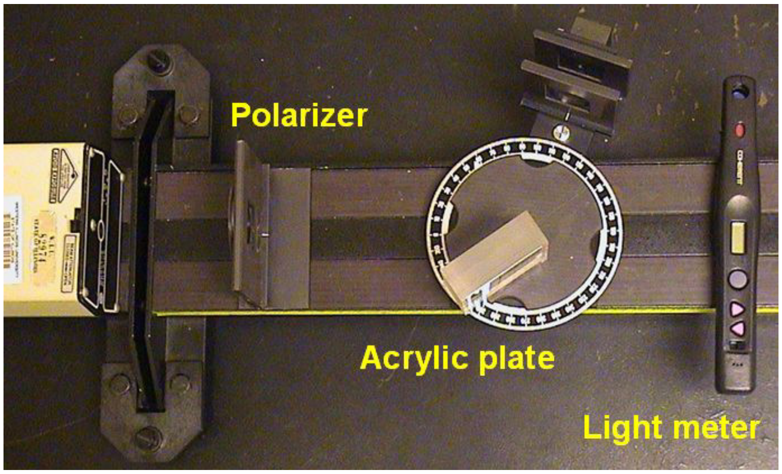


Fig. 2 Observing reflection of a polarized light

4) Wave Plates [Room 312]

The slow axis of each wave plate is supposed to be parallel to the line connecting the 0º and 180º marks on the wave plate. The fast axis connects the 90º and 270º marks.

a) Quarter wave plate

The 140 nm retarder is almost a quarter wave plate (QWP) for the He-Ne laser. Position two polarizers on the optical bench so that the laser beam passes through both of them. The polarizer closer to the laser is the polarizer and the other is the analyzer. Set the polarizer at 0º. Attach the QWP to an element holder and position it between the polarizer and the analyzer. Set the QWP at 45º and use the analyzer to show that the beam transmitted through the QWP is circularly polarized. A polarized light is circularly polarized if its intensity transmitted through an analyzer is the same at all analyzer angles. The circular polarization may not be perfect because the QWP is not exactly a QWP for the light at the wavelength of 633 nm.

Please set the QWP at an angle of 0º. Analyze the polarization of the light passing through the QWP. Repeat for a QWP angle of 90º. Why does the QWP have no effect at these angles?

Please set the QWP at 20º. Use the analyzer to show that the light is elliptically polarized.

b) Half wave plate

Please use polarizer #1 as a polarizer and polarizer #2 as an analyzer. Place two QWPs on the same element holder, one attached on the front and the other on the rear, and position them between polarizers #1 and #2. If the two QWPs are oriented at the same angle they will form a half wave plate (HWP). Note that it is not quite a HWP for the He-Ne laser light, but it is very close.

Please note that although in principle the slow axes of the two QWPs should both be in the 0º-180º line, however, I found that for the two QWPs we are currently using, one of them has its slow axes actually in the 90º-270º line. This is caused by the carelessness of the maker. To correct this, please always let the 90º line of the second QWP overlapped with the 0º line of the first QWP. The weirdest error I have ever heard is that your doctor can take someone else's radiology image as yours (RadioGraphics 19,765 (1999)). Being a good physicist requires that you are always skeptic.

Please set the polarizer and analyzer at angles of 0º. Set the HWP at an angle of 45º (This means that the front QWP is set at 45º). Rotate the analyzer and observe the intensity of the transmitted beam. You should find that the beam passing through the HWP is still linearly polarized, but its polarization direction has been rotated by 90º.

Now please set the HWP at 20º. Use the analyzer to show that the light passing through the HWP is linearly polarized but has been rotated by 40º. Repeat for a HWP angle of 60º, and the light will be rotated by 120º.

What general conclusions can you draw about the effect of a HWP? If a laser beam is linearly polarized, how could you rotate the polarization direction by any desired amount?

5) Calcite crystal [Room 310]

Please let the He-Ne laser beam pass through the large calcite crystal. This is still in Room 312. I got this precious treasure from a flea market in Monterey, California. Please observe the transmitted light and confirm that the light is split into two beams. Now please use the polarizer to check the polarization of the two transmitted beams. What is the relation between their polarizations?

Now let us move to Room 310. Please put the polished calcite crystal on a page of paper and see the transmission of letters without using a polarizer. Rotate the crystal and observe the motion of the two images. You may maximize the separation between the two images by choosing a different set of surfaces of the crystal. Now please observe the two images of the letters through a polarizer. Rotate the polarizer and notice the appearance of the images. Explain what you see through the calcite crystal without a polarizer and with a polarizer.

Please put the crystal on a picture of a bird, and see the transmission of the picture through a polarizer while rotating the polarizer back and forth. What you see is fascinating, although you are not a small child any more.

6) Crossed polarizers [Room 310]

Please turn on the incandescent light in the wood box and look at it through two polarizers. Adjust the polarizers until they are exactly crossed and the light coming from the source is extinguished. Place each of the following objects *between* the polarizers and *rotate* the object. You will see that light is transmitted in very interesting ways. Please take pictures when possible.

a) A plastic protractor.

b) A U-shape plastic — squeeze it and see the stress-induced bands.

c) A small plastic box.

d) Pieces of cellophane tape on glass.

e) A sheet of mica — mica has three different indices of refraction, and is thus a biaxial crystal. What do you see if you put your eyes closer?

f) Karo corn syrup — rotate one of the polarizers and observe the color changes of the syrup. Explain why you see different colors for the transmitted light from the syrup when you are rotating the polarizer.

Some pictures are shown in Fig. 3. They are sequentially 1) plastic protractor, 2) squeezed U-shape plastic, 3) plastic box, 4) cellophane tapes stuck on glass, 5) cellophane tapes wrapped on glass, 6) mica, 7) Karo corn syrup (my fingers are on the bottom), 8-9) Karo corn syrup (with one polarizer rotated), 10) calcite (no polarizers), 11) calcite (with one polarizer passing only the *e*-ray), and 12) calcite (with one polarizer passing only the *o*-ray).

Fig. 3 Appearance of some objects between polarizers