Laser Academy – Lasers and Optics Laboratory Manual

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Introduction

The program you have signed up for at Queensborough Community College is designed to introduce you to careers in technology in the areas of lasers, fiber optics, and computer-controlled mechanical design. Throughout the course, you will be introduced to, and you will perform, some of the hands-on skills needed as part of a basic education in these technology fields. This means that you will be working with state-of-the-art equipment which is both costly and fragile. You must be careful when operating any of the equipment set up for your experiments in our labs, because if you are not careful you could be injured and the equipment could become damaged. This course is intended to be fun and educational for you, but it is not meant to be "playtime." When you are on our campus you will be treated with respect and we expect you to behave in a respectful manner in return. The following guidelines will help you to use the equipment properly and safely:

*when you enter the room and find the equipment set up on the lab bench, DO NOT TOUCH anything until the instructor has explained the experiment and the safe use of the equipment;

*once instructed on how to use the equipment properly, do not deviate from these instructions – do not try anything that you were not told to try without asking first;

*do not force anything to move beyond its normal operating range. In other words, if a knob doesn't seem to want to turn anymore in one particular direction, do not try to force it;

*do not use the lab equipment for anything other than the experiment you are supposed to be doing. You will receive and sign a separate sheet dealing with laser safety, but it is so important that it will be repeated here: NEVER AIM A LASER AT ANOTHER PERSON. Do not fool around in any way in the lab – this is how accidents happen. Anyone caught behaving carelessly with a laser or any other piece of equipment will be expelled from the program – no warnings;

*behave in a mature way when in the lab – don't run around, play games, leave lab stools in the middle of the aisle, or soda cans and plates laying around. When you are finished eating, dispose of your garbage immediately so that accidental spills do not occur. If the room is left dirty each day when class is over, the food will be discontinued.

Your instructors for this course are highly trained professionals who have spent many years working in the areas of science which they will be teaching you. Most of your instructors have Ph.D.'s in science, which means around 9 or 10 years of full-time school after high school, plus several years of working in industry and in the University. When you have a question, please address them by name, for example, "Dr. Engelberg" or "Mr. Taylor," or you may call them "Professor." It is not acceptable to call your instructors "Hey Mister" or "Miss." "Miss" is what you call a little girl, not a person with a Ph.D. in Science! Please show your instructors the respect they have earned from their many years of training and professional experience.

Please be ready to begin as soon as your bus drops you off at Queensborough. There is no time to run errands or go wandering around the campus once you arrive. You will have a chance to have a snack and chat with the other students before the actual work begins, but everyone must arrive at the lab promptly or else some will miss the explanation of the lab exercise for that week. The best way for everyone to make the most of the time you have with your instructors is to arrive on time.

Please read the write-up for the experiment you will be doing each week in advance. If you have read the background material and instructions completely before you arrive, you will better understand the remarks made by the instructor and you will be able to ask questions about anything that isn't clear to you. If you wait until you arrive to begin reading the experiment for that week, you will waste valuable time and might not have time to complete the experiment. Also, you will not understand the instructor's remarks as well as you would have if you were prepared.

Finally, please try not to miss too many sessions. This is a college credit-bearing course, and you cannot receive a passing grade if you have excessive absences, no matter what the excuse is. Also, each week you miss is one more skill that you will not learn! Try to make to most of this opportunity. We created this program to help you learn about careers in technology so that when it comes time to decide on a career and college, you will know much more about what is out there for you. We are here to help and we care about your education, so please, ask questions, show enthusiasm, and enjoy the course!

Laboratory #1: Alignment Skills Exercise

Background

Laser beam alignment, and alignment of optical components in general, is a very important skill for anyone wishing to work with optical systems. "Alignment" means getting the laser beam to follow the path that you need it to follow in order for a device or experiment to work properly. For example, when a laser is being built, usually another laser is used to align the new laser in order to get it running for the first time. Alignment is also important for people using surveying equipment which can contain lasers; in order to make a measurement, the laser must be aimed at the correct target. Finally, if you are setting up an optical experiment involving many mirrors, beam splitters, lenses, and other components, they all must be aligned so that the laser used in the experiment will be properly directed through the various mirrors and lenses.

Optical alignment requires skill, but also patience and steady hands. It requires the use of a specific method, not just random adjustments in the hope of stumbling onto the right position. It also requires very small corrections when the system gets close to final alignment, so it is important not to get impatient and tweak things too much when you start getting close! If you follow the method described in this write-up, you will begin to develop good alignment skills. It, of course, takes a lot of practice to get proficient at it, but every time you do it, it gets a little easier than it was the previous time. If you have trouble, don't give up! Take a break, then ask for help from the instructor.

Procedure

In this exercise you will learn to use mirrors to direct a laser beam along a specific axis and through two pinhole apertures. This is very much like the process used to align a new laser that is being built. This experiment is divided into two parts. In part one, you will align the laser beam to pass through the bottom set of pinholes, which will be roughly the same height as the laser. In part two, you will vertically raise the laser beam level to pass through a second set of pinholes located right above the set used for part one.

The experimental setup is shown below in Figure 1:

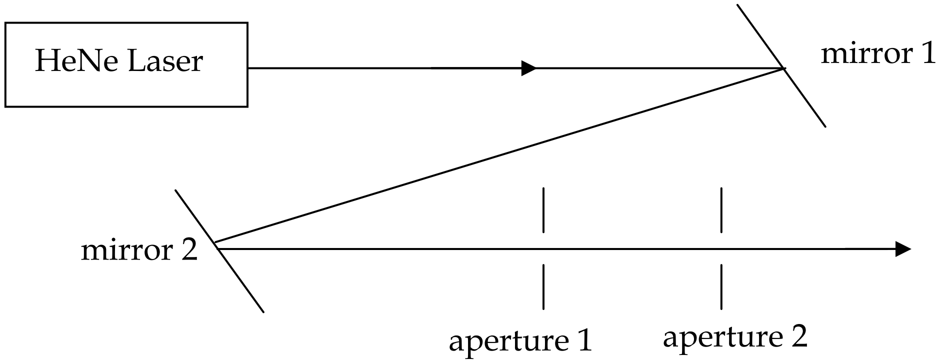


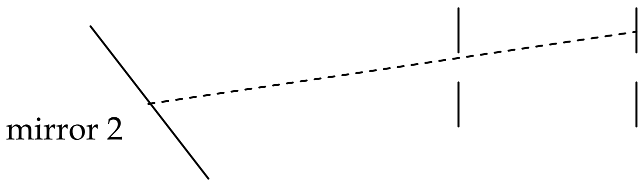
Figure 1

Part One

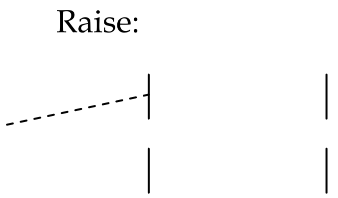
As shown in Figure 1, you will need to manipulate two mirrors in order to make the laser beam pass through both pinhole apertures. This is because you need to control both the position and the tilt angle of the laser beam. Do not make any adjustments on the laser itself; this was set by the technicians and should be left alone. Also, do not move the pinholes.

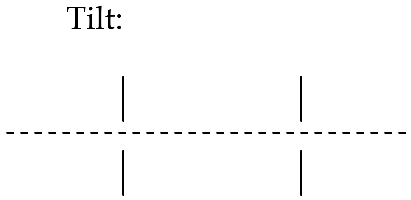
First, you will use the horizontal mirror adjustments (located on the lower left corner of the mirror mounts) to line the beam up with the bottom set of pinholes. By looking at Figure 1, you can see that the horizontal adjustment of mirror 1 will control the position of the laser beam as it strikes the first pinhole, and the horizontal adjustment of mirror 2 will control the tilt angle of the laser beam as it strikes the first pinhole. You must alternate between adjusting the position and the tilt angle until the beam is lined up with the lower pinhole; the vertical height still needs to be adjusted, but we will get to that soon. Hints about how to do this alignment will be given in class.

As an example, let's say that your laser beam is misaligned as follows:



The beam is passing through the first aperture, but is not passing through the second aperture. The way to fix this alignment problem is to first <u>raise the position</u> of the laser beam <u>using mirror 1</u> and then <u>tilt</u> the laser beam downward <u>using mirror 2</u> to obtain a level beam which should be horizontally lined up with the bottom pinhole:





Note that the first step of raising the position of the laser beam appears to make the alignment problem worse, but it is <u>the only way to fix the alignment problem</u>. Keep this example in mind as you work with your mirrors - when something is misaligned, you must adjust both <u>position and tilt</u>.

Part Two

Once the horizontal alignment is completed, you must repeat the same procedure using the vertical adjustment knobs. Do not touch the horizontal knobs during this part or you will lose the alignment you just achieved! Use the vertical knobs and the same procedure to make the beam pass through both lower pinholes.

Once this is done, the next step is to raise the vertical level of the laser beam and make it pass through the top set of pinholes. Use the same procedure as you just used for the lower set of pinholes; again, do not touch the horizontal adjustment knobs! Alternate between adjusting tilt and position until the beam passes through both pinholes.

Part Three

If you have successfully completed parts one and two of the experiment, try this: align the laser beam so that it passes through the bottom pinhole on the first aperture and the top pinhole on the second aperture. Then, reverse this: make the beam go through the top pinhole on the first aperture and the bottom pinhole on the second aperture.

Laboratory #2: Refraction and Total Internal Reflection

Refraction - Background

In this exercise you will learn how light bends when it goes from air into another material, like glass or plastic. This “bending” is called refraction – it’s the reason why, if you are standing in a pool of water and you reach for something at the bottom, like a coin, the coin isn’t sitting where you think it ; the light bends, but your brain assumes the light is traveling in a straight line (see Figure 1). Refraction is important because without it, optical fibers would not work. What you will learn in this experiment relates directly to how optical fibers are designed to transmit information.

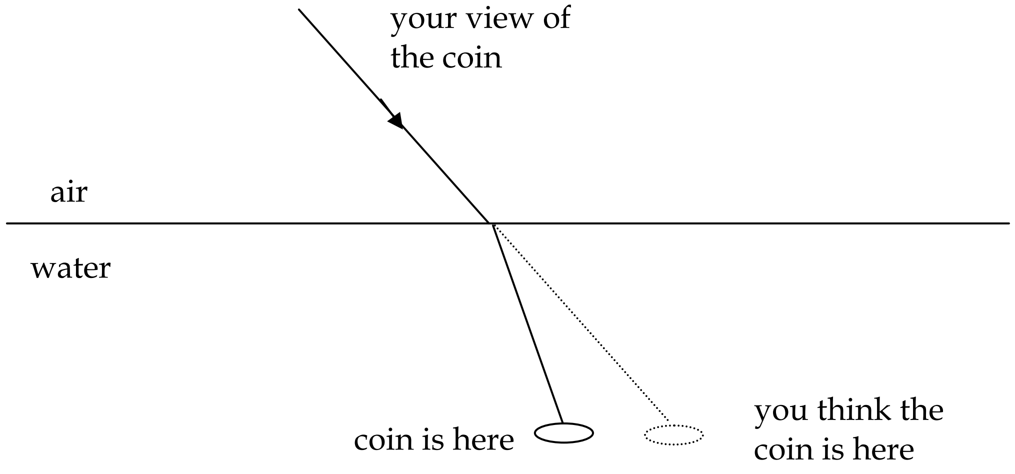


Figure 1 – Illustration of how light bends when it crosses the boundary between two materials

Materials have what is called an <u>index of refraction</u> which tells us how much, and in what direction, the light will bend when it enters that material. The index of refraction in a perfect vacuum (totally empty space) is 1.000. In air it is close to, but not exactly, equal to one – it is 1.0003, but for practical purposes we can use 1.0 for the index of refraction of air. In glass, the index of refraction is usually around 1.5, and in water, it is 1.33. Notice how the index of refraction for various materials is greater than 1. This is because the index of refraction is defined as the ratio of the speed of light in vacuum to the speed of light in the material. Light travels faster in vacuum than in any other material, so that means the index of refraction must always be greater than 1 for all real materials.

If light hits a boundary between glass and air, as shown in Figure 2, the light will bend as it crosses the boundary – it will change directions, just like it did in the swimming pool example. The direction of the light is described by the angle at which it strikes the surface, measured with respect to the surface normal (a line perpendicular to the surface), as shown in Figure 2.

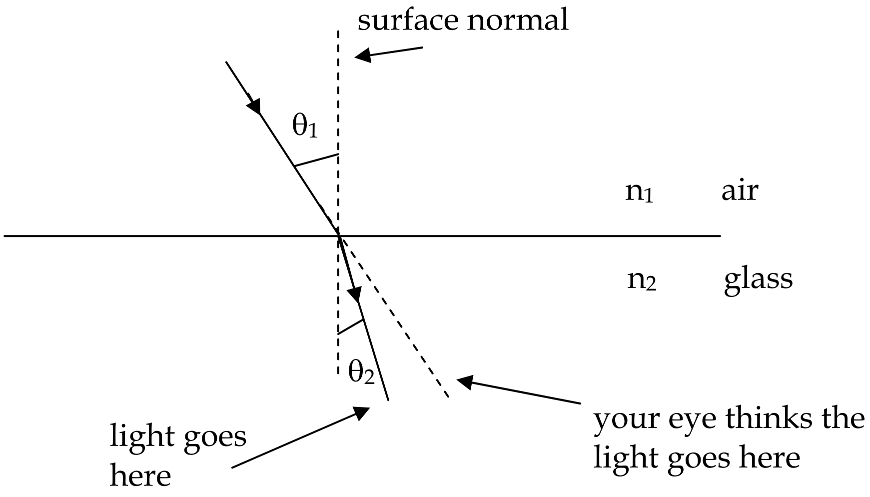


Figure 2- Light coming from air and entering a piece of glass gets bent at the surface.

The real path of the light in the glass is shown by the solid line, while the path your eye thinks the light takes is shown by the diagonal dotted line.

There is a simple way to predict how much the light will bend when it crosses the boundary between two materials. If the light is incident from a material with index of refraction n_1 at an angle of θ_1 and, after it crosses the boundary into a material with index n_2 it is at an angle θ_2, the equation relating all these quantities is called Snell's Law:

$$\mathbf{n_1 \sin\theta_1 = n_2 \sin\theta_2}$$

In this exercise you will figure out the index of refraction of a piece of glass by tracing a light ray through it and measuring the angles θ_1 and θ_2.

Part I – Refraction - Procedure

In this part of the lab, you will draw a diagram like that of Figure 2 using a real piece of glass and a laser beam. Since it is not possible to "trace" the path of the laser beam with your pencil, you will first mark the path with pins, then remove the pins and draw straight lines through the pin holes in the paper. Follow these step-by-step instructions:

1. Place the glass plate on a sheet of paper over the cork board. Trace the outline of the glass on the paper.

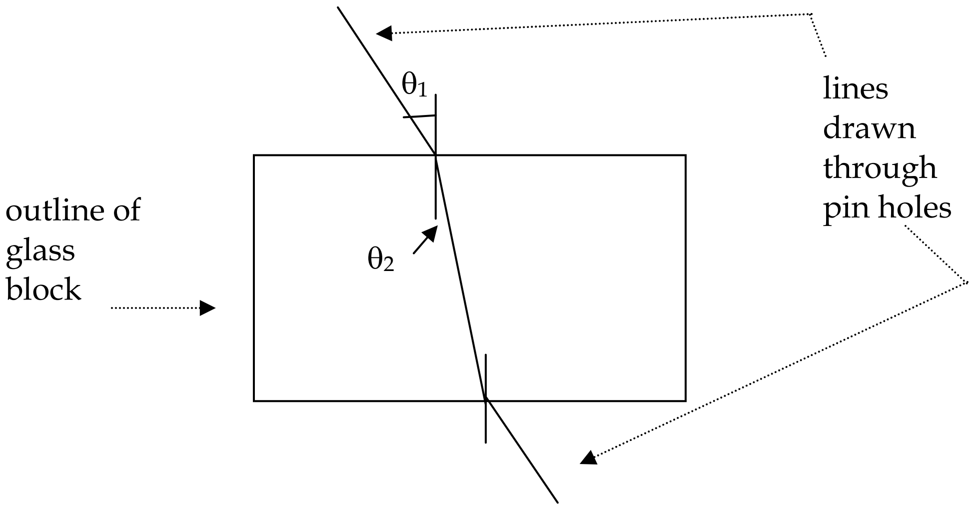
2. Turn on the laser and aim it at the glass so that it is passing through the front and back surface of the glass at some angle other than straight-on.

3. Mark the beam path on the paper by inserting pins along the beam path on both sides of the glass. Two pins on each side will be enough for you to mark the path of the laser beam.

4. Remove the pins and the glass block and draw straight lines through the pin holes up to, but not through, the glass block outline.

5. Now draw the laser beam path through the glass by connecting the entry and exit points (connect the two lines you drew in step 4).

6. Draw a line perpendicular to the glass surface at the point where the beam entered the glass and again where it exited the glass. Your paper should now look something like this:



Measure the angles θ_1 and θ_2 and, using $n_1 = 1.0$, use Snell's Law to calculate the index of refraction of the glass.

Total Internal Reflection - Background

As you can see from Part I, when the light entered the glass, its angle with respect to the surface normal decreased; in other words, $\theta_1 > \theta_2$. As you can see from your drawing, when the light exited the glass on the other side, its angle with respect to the normal increased compared to when it was inside the glass: $\theta_1 < \theta_2$. This makes sense because when the light comes back out of the glass, it should be at the same angle it was at when it entered (θ_1), so it must bend away from the normal when it exits the glass because it bent towards the normal when it entered the glass.

The result of all of this is that when light goes from a high-index material to a low-index material, its angle will always increase as it makes the transition. So, when going from glass to air, if we keep increasing the angle at which the light hits the boundary, the exit angle will have to keep increasing. This can't go on forever; we will eventually reach the point where the exit angle will be 90 degrees – the beam will be parallel to the glass surface. If we increase the angle farther, the light will not be able to exit the glass – it will be reflected back into the glass as if the glass-air boundary were like a mirror. This is called **total internal reflection** (TIR) and it is the reason that optical fibers are able to transmit light efficiently. The "core" of the fiber contains a high-index material and the surrounding "cladding" is made of a low-index material – the light therefore gets trapped in the core and totally internally reflects as it travels down the fiber.

The condition for TIR comes from Snell's Law…we simply plug in $\theta_2 = 90$ degrees and solve for θ_1, which is then called the "critical angle" – it is the angle above which TIR will occur. So,

$$\sin\theta_c = 1/n_2$$

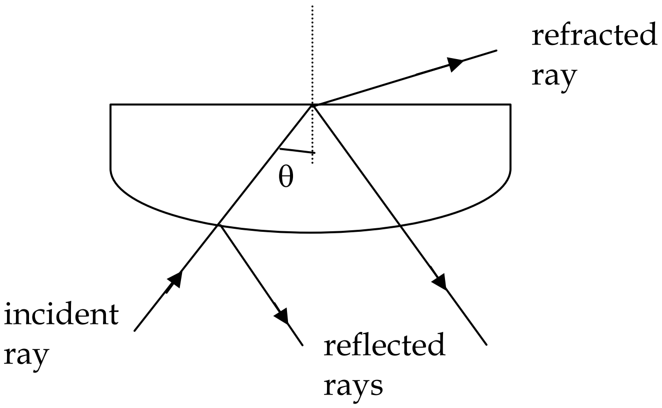
if we are going from glass into air, and n_2 is the index of the glass. This means that any light which strikes the boundary at an angle greater than θ_c will be reflected back into the glass. If it strikes the boundary at an angle less than θ_c, it will still be able to cross the boundary.

Part II – TIR - Procedure

You will use TIR to find the index of refraction of a plastic semi-circle.

1. Place the semi-circle on a sheet of paper over the corkboard and trace its outline. Remove the plastic temporarily. Mark the center of the flat side of the semi-circle. Draw a normal (perpendicular line) through that center. Put the plastic back on its outline.

2. Aim the laser through the semi-circle from the curved side and try to hit the center of the flat side. You should get something which looks like this:



Note that, even before you reach the critical angle, there will be a reflected ray from the flat side and from the curved side. This is normal; light always reflects a little bit when it hits a piece of plastic or glass. This is NOT TIR though as long as the refracted ray is still coming out on the other side.

3. Increase the angle of incidence θ by rotating the paper and the semi-circle together until the refracted ray is parallel to the flat side of the semi-circle. Make sure the laser is still hitting the center of the flat side as you rotate! The

point at which the refracted ray starts to disappear (when it is parallel to the flat side) is the onset of TIR. At this point, stop rotating, mark the incident ray with pins, and remove the semi-circle.

4. Connect the incident ray to the normal on the flat side and measure the angle that the incident ray makes with this normal (the angle marked "θ" in the drawing above). This is the critical angle θ_c. Use it in the equation

$$\sin\theta_c = 1/n_2$$

to calculate the index of refraction (n_2) of the plastic semi-circle.

Laser Academy

Laboratory #3: Lenses, Image Formation, and Telescopes

Background

In this exercise you will learn how lenses are used, individually and in combination, to form images. You will also build a simple telescope and see exactly what it does to the image of the original object. Lenses can be either converging or diverging, depending on what they do to light rays which hit them. If parallel rays strike a converging lens, they get focused to a point by the lens, as shown in Figure 1. If parallel rays strike a diverging lens, they spread out after passing through the lens, but they look like they came from a single point in front of the lens, as shown in Figure 2.

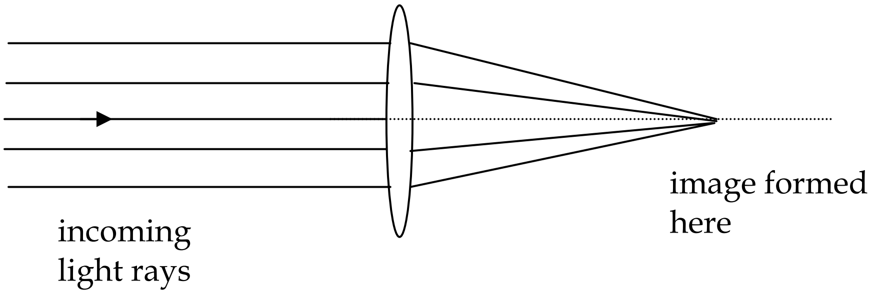


Figure 1 – Image formation by a converging lens. This image is a “real” image.

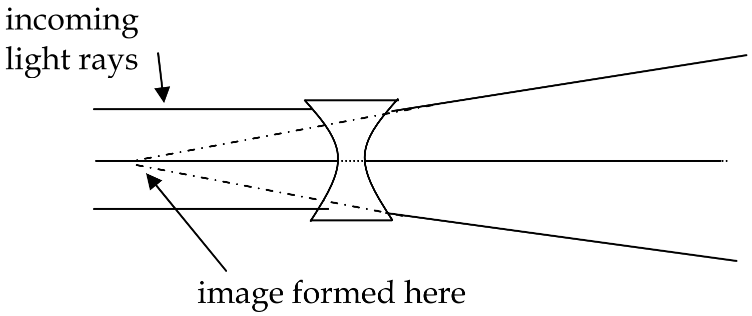


Figure 2 – Image formation by a diverging lens. This image is a "virtual" image.
The equation which tells us where an image is formed for a given lens is:

$$\frac{1}{f}=\frac{1}{o}+\frac{1}{i}$$

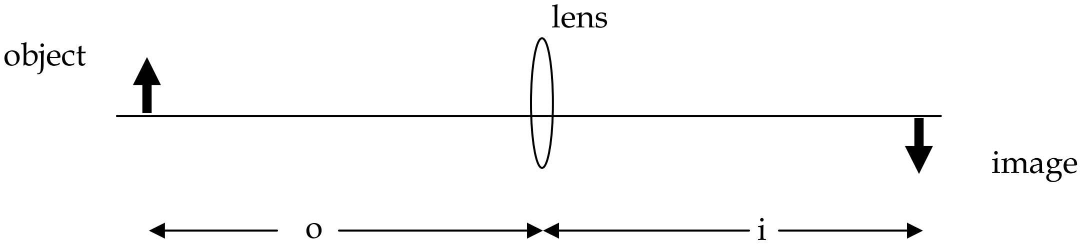


Figure 3 – Diagram illustrating the quantities given in the lens equation.

where **f** is the focal length of the lens, **o** is the object's distance from the lens, and **i** is the image's distance from the lens. If you place the object very, very far away from the lens, then **o** will be very large and 1/**o** will be very small, so the image distance **i** will equal the focal distance **f**. This is the example shown in both Figures 1 and 2; an object which is very, very far away sends light rays to the lens which are almost parallel and can be considered parallel.

The equation above can be used for both converging and diverging lenses. If the lens is converging, the focal length gets plugged in as a positive number; if the lens is diverging, the focal length gets plugged in as a negative number. Then, if the image distance **i** turns out to be positive, the image is located on the opposite side of the lens compared to the object. This is called a real image. If the image distance **i** turns out to be negative, then the image is located on the same side of the lens as the object. This is called a virtual image. The difference between a real image and a virtual image is simple: a real image has real light rays passing through it, whereas a virtual image is an image that appears to be at a certain point in space, but the light rays don't actually go to that point. Figure 1 shows an example of a real image, whereas Figure 2 shows an example of a virtual image – the rays do not actually converge on the opposite side of the lens, but they appear to converge on the object side of the lens.

We will use different lenses and different object distances to find the focal lengths of some individual lenses, and then we will use some lenses in combination to build a simple telescope. The way to deal with combinations of lenses is simply to take them one at a time. You apply the lens equation to the object and the first lens, and you find the image location as if the second lens weren't there. Then, you use the image from the first lens as the object for the second lens, and you apply the lens equation again. This means that you must measure the distance **o** from the second lens to the image from the first lens (which is now your new object). The value for **i** that you get this time is the location of the final image for the two-lens combination. If you had more lenses in combination, you would just keep on applying the lens equation to each one in turn. Figure 4 illustrates the two-lens example.

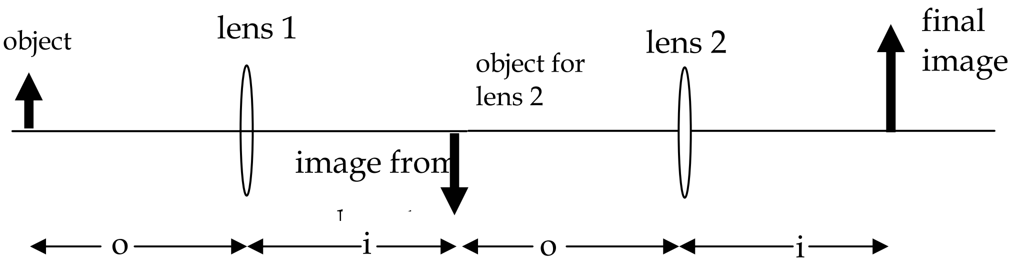


Figure 4 – Illustration of a two-lens combination.

A simple telescope can be made with a two-lens combination. A telescope takes parallel input rays (because it looks at stars that are very far away) and magnifies them, producing parallel rays at the output. Because the output rays are parallel, your eye does not visualize the image from a telescope as being at a specific location; rather, it looks lie the planet or star is floating "out there somewhere." You will not see this effect in the lab demonstration because the telescope you will build will be used to view an object close by, but if you ever look through a telescope at a planet, you will notice that you have no idea how far away the image of the planet is!

The way to construct a two-lens telescope is simple; remember that we said that parallel input rays focus at the focal point of the lens? Well, if you apply that theory to both ends of the telescope, you will see that you will get parallel rays out for parallel rays in when the lenses are separated by the sum of their focal lengths. This is illustrated in Figure 5.

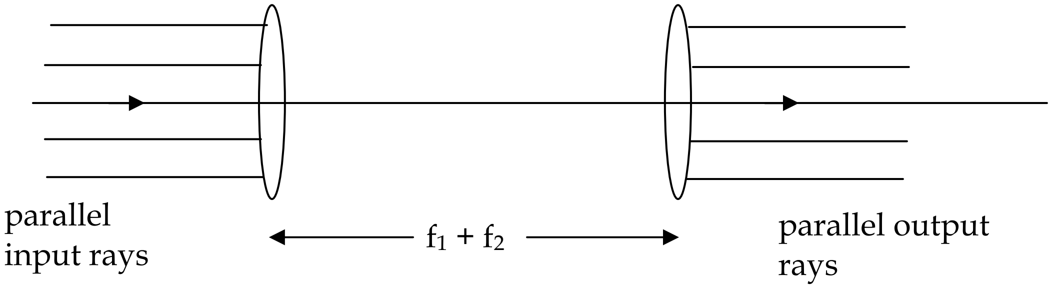


Figure 5 – A two-lens telescope. The lenses have focal lengths f_1 and f_2; they are separated by a distance $f_1 + f_2$ to produce parallel output rays when parallel input rays come into the telescope.

Procedure

Single Lens

1. Place your light source as far away from the lens as you can on the optical rail. Use an f = 10 cm lens and find a clear image of the light

source; measure the distance of this image from the lens; it should be 10 cm, the focal distance, because **o** is large in this case. How close is your measured value to this theoretical value? Is the image rightside-up or upside-down? Take notes in the spaces provided here.

2. Replace the 10 cm lens with the 5 cm lens and repeat.

3. Put the 10 cm lens on the rail and put the light source 20 cm in front of it. Find the sharpest image and measure its distance from the lens.

4. Use the lens equation with **o** = 20 cm and **f** = 10 cm to calculate what **i**, the image distance, should be. Compare this with your measured result.

5. Repeat step 3 with the light source located 30 cm from the lens.

Two lenses

Place the light source 20 cm in front of the 10 cm lens. Place the 5 cm lens 30 cm behind the 10 cm lens. Find the sharpest image formed by the second lens and measure its distance from the lens. Use the lens equation to determine this image distance.

Simple Telescope

Use the 20 cm lens and the 5 cm lens to construct a telescope using the guidelines given in the background section. If it works, you should be able to look through the 5 cm lens back towards the light source and see an inverted image of it. Is the image larger than the source or smaller?

Laboratory #4: Reflection of Polarized Light

Background

The purpose of this laboratory experiment is to study the reflection characteristics of polarized light as its angle of incidence and polarization are varied. Whenever light is incident on an optical surface there are three things which can happen; the light can be reflected, transmitted, or absorbed. For most optical surfaces all three of these things happen, but usually one of them will dominate. For example, you know that a glass window transmits light, but actually it reflects 4% of the light which is incident upon it. Similarly, a mirror is primarily a reflecting surface, but a very small percentage of the light is transmitted through most mirrors. For purposes of this lab, we will be ignoring absorption.

Polarization deals with which way the electric field part of the light is oscillating. Light is an "electromagnetic wave" which contains both electric and magnetic fields that oscillate (move up and down) as they travel; they look like the kind of wave you'd see if you tied a rope to the wall and shook your hand up and down. This type of wave is called sinusoidal and looks like the wave shown in Figure 1.

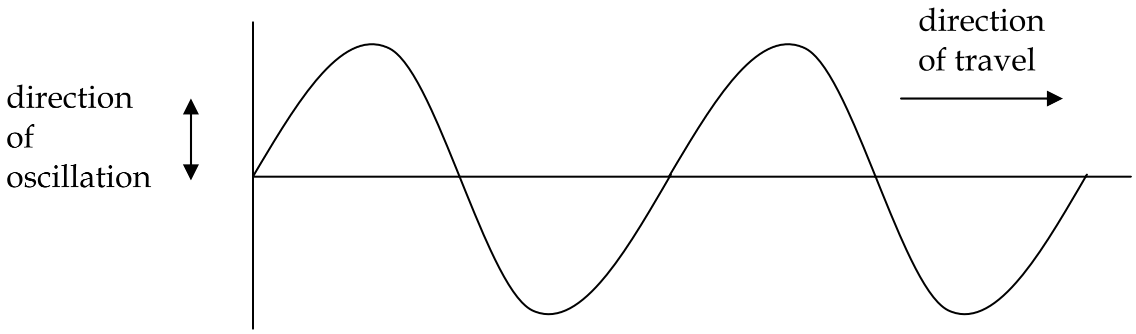


Figure 1 – An example of a sine wave; the electric and magnetic fields which make up a light wave oscillate like this as they travel.

The wave shown in figure 1 is called a transverse wave because the direction of oscillation is perpendicular to the direction of travel of the wave. Now, remember that light travels in three-dimensional space, whereas the pictures we draw here are only two-dimensional. The actual light wave can oscillate in the direction shown in Figure 1 (up and down on the page), or it can oscillate in and out of the page, or any direction in between. If the direction of oscillation of the wave varies randomly as the wave travels, and it does not favor any one particular direction, then the light is unpolarized.

A polarizer is an optical component that restricts the direction of oscillation of the wave to a particular direction. There are many ways to do this, but in this lab, we will only be concerned with what is called linearly polarized light, which means that it is either vertically or horizontally polarized. If the light is vertically polarized, for example, it can only oscillate in the vertical direction. If it is horizontally polarized, it can only oscillate in the horizontal direction. In this lab, you will see that polarization affects the way light reflects off of a piece of glass and we can use this property to turn unpolarized light into polarized light. Let's now take a look at what happens when light reflects off of a boundary between two different materials, for example, glass and air.

The amount of reflection and transmission which occurs at the boundary between two materials is determined by their indices of refraction (recall from lab #2). For normal incidence, meaning the light strikes the boundary perpendicular to it, or "straight on," the reflectance R (defined as the reflected beam intensity divided by the incident beam intensity) is given by

$$R = \{[n_1 - n_2]/[n_1 + n_2]\}^2$$

Where n_1 and n_2 represent the indices of refraction for the two materials; it does not matter which is the "entrance" media and which is the "exit" media because, as you can see, the equation is symmetric in n_1 and n_2 , meaning that if you swap them it makes no difference. So, for the example of ordinary window glass, if we use an index of refraction n_1 = 1.5 and the index n_2 = 1.0 for air, the above equation tells us that the reflectance at the air/glass interface is 4%. This means that any time light hits regular window glass, 4% of it is reflected back rather than being transmitted through.

Fresnel's Laws of Reflection tells us that when the angle of incidence is anything other than normal (zero degrees) the reflectance will depend on the polarization of the incident beam; this means that the amount of reflected light will be different for horizontal polarization than for vertical polarization. The way the light will behave as the angle of incidence is changed is shown in Figures 2 and 3. Figures 2 and 3 show reflectance as a function of angle of incidence for both "s" and "p" polarizations (this is the short-hand way to denote vertical and horizontal polarization directions). Figure 2 represents the situation when the light is coming from air and reflecting off of the glass surface, whereas Figure 3 shows the case where the light starts in glass and reflects off of the boundary with the air. Notice that Figure 3 shows θ_c, the critical angle (recall from lab #2). Beyond the critical angle, the light cannot escape the glass; it experiences total internal reflection.

Figure 2 – Reflectance as a function of angle of incidence for the case of light coming from air and reflecting off of glass.

Figure 3 – Reflectance as a function of angle of incidence for the case of light coming from glass and reflecting off of the boundary with air.

Note that in both figures 2 and 3 for p-polarization there is an angle for which the reflectance is equal to zero. This angle is called Brewster's angle and it is defined by the equation

$$\tan \theta_B = n_2/n_1.$$

Recall from lab #2 the formula for the critical angle:

$$\sin \theta_C = n_2/n_1.$$

We will not be studying total internal reflection (TIR) during this laboratory exercise, but you should recognize that TIR is the reason why the curve in Figure 3 does not extend out to 90 degrees like the one in Figure 2.

So, we see that there is an angle, Brewster’s angle, at which p-polarized light can be made to disappear when it reflects off of a surface, leaving only s-polarized light. This property of reflected light is very useful for generating polarized light; if an unpolarized beam of light is made to reflect off a surface sitting at Brewster's angle, the resulting reflected light will be linearly polarized. Specifically, it will be s-polarized light. This method is sometimes used to ensure that the output beam of a laser is linearly polarized. This property is also the reason why polarized sunglasses work well. When you go outside and see a lot of glare, that usually comes from sunlight reflecting off of buildings, roadways, and cars. This reflected light will be mostly s-polarized. Polarized sunglasses are designed to block this s-polarized light, leaving only p-polarized light. This reduces glare and makes everything easier to look at. In this lab, you will be conducting a series of experiments which will allow you to observe and determine Brewster's angle for a glass block.

Procedure

You may enter your data in the table provided below. You will do a series of experiments to try to experimentally reproduce the curves shown in Figure 2. The experimental apparatus should look like Figure 4. The half-wave plate enables you to rotate the polarization of the laser beam from vertical to horizontal and back again. The linear polarizer is there to check to make sure the polarization is as you think it is!

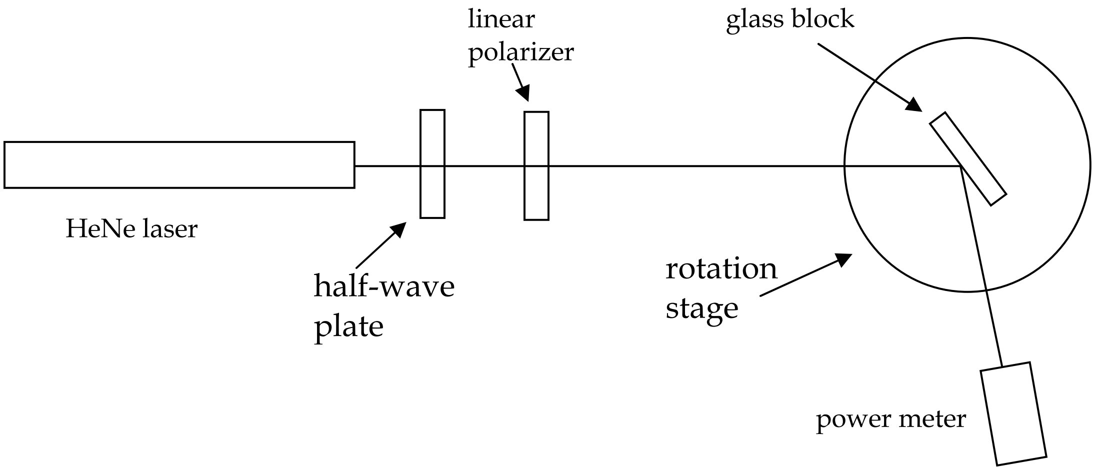


Figure 4 – Experimental set-up for reflectance measurements as a function of angle of incidence.

Part I.A. S-Polarization (perpendicular) Reflection as a Function of Incident Angle

1. The light incident on the glass block is initially set to be vertically polarized. Note the angle on the half-wave plate and linear polarizer. If the rotation stage is set at 0 degrees, the laser beam should be

retroreflecting (going back exactly the way it came). If it is not, fix it at this time.

2. Rotate the rotation stage in 5-degree increments and align the power meter with the reflected beam each time. Record the power reading for each increment. Take data up to an angle of incidence of 80 degrees.

Part I.B. P-Polarization (parallel) Reflection as a Function of Incident Angle

1. Rotate the half-wave plate by 45 degrees; this rotates the polarization of the laser beam by 90 degrees. The beam is now horizontally polarized, in the plane of incidence. Rotate the linear polarizer 90 degrees to confirm this.

2. Repeat step 2 of Part I.A.

Part I.C. Unpolarized Light (simulation) Reflection as a Function of Incident Angle

1. Rotate the rotation stage of the half-wave plate to read 22.5 degrees. This causes the beam to polarized at an angle of 45 degrees with respect to the horizontal, so it is half p- and half s-polarized.

2. Repeat step 2 of Part I.A.

Part II. Reflection as a Function of Polarization Angle at Fixed Angle of Incidence

1. Set the rotation stage of the glass block at an angle of 57 degrees. Leave it at this setting for this part of the experiment.

2. Rotate the half-wave plate from 0 to 45 degrees in 5-degree increments and record the power readings of the reflected beam. You may enter your results in the table below.

Results

Your experimental results should look like the results shown in Figure 2; the s-polarized light power should gradually rise with increasing angle of incidence. The p-polarized light reflected power should go to zero at some angle – this is Brewster's angle. Calculate what is should be from the formula above, using 1.5 as the index of refraction for the glass and 1.0 for air, and compare your calculated value to your experimental value. What should the data from part C do? Well, since it contains an equal mix of s- and p-polarized light, it should look like it would fit in between the curves of Figure 2. Finally, the data from Part II should show you that s-polarized light will reflect off of the glass block when it is set at Brewster's angle, but p-polarized light will not. This means your reflected power when the half-wave plate is set at zero degrees should be high and the reflected power when the half-wave plate is set at 45 degrees should be close to zero.

Table for Results of Part I:

Theta	Power - Part I.A.	Power - Part I.B.	Power - Part I.C.
5			
10			
15			
20			
25			
30			

35			
40			
45			
50			
55			
60			
65			
70			
75			
80			

Table for Results of Part II:

Theta	Power
5	
10	
15	
20	
25	
30	
35	
40	
45	

Laboratory #5: Monochromators

Background

In this exercise you will learn to use a monochromator to determine the wavelength of several different colors of light emitted by the Helium-Neon laser. The Helium-Neon, or HeNe laser, is the laser used in supermarket scanners, surveying equipment, and some laser pointers. It most commonly emits red light, but the ones you will use today are tunable HeNe's and are capable of producing red, orange, yellow, and green light. The monochromator is a device which measures the wavelength content of light entering it. All light, including laser light, consists of a spread of wavelength values rather than just a single wavelength value. Most conventional light sources, like ordinary lightbulbs, emit many wavelengths across the entire visible spectrum. Lasers emit relatively pure light, containing a small range of wavelength values. The monochromator can measure the wavelength spread for each light beam entering it. Figure 1 shows what is inside the monochromator.

The grating in Figure 1 separates the incoming light according to wavelength (color); as the light travels away from the grating, the colors spread out in space, so that when they get to the plane mirror by the exit slit, only one wavelength will pass through; the others will be blocked. When you turn the knob on the monochromator, you are rotating the grating so that different wavelengths become aligned with the exit slit and come out of the monochromator. In this way, you can read the dial by the knob and know exactly what wavelength of light is exiting the monochromator.

The wavelength spread contained within the laser beam will not contain equal amounts of power at all wavelengths; the power distribution will look something like that shown in Figure 2.

Figure 1 – Schematic of the key elements contained inside a monochromator.

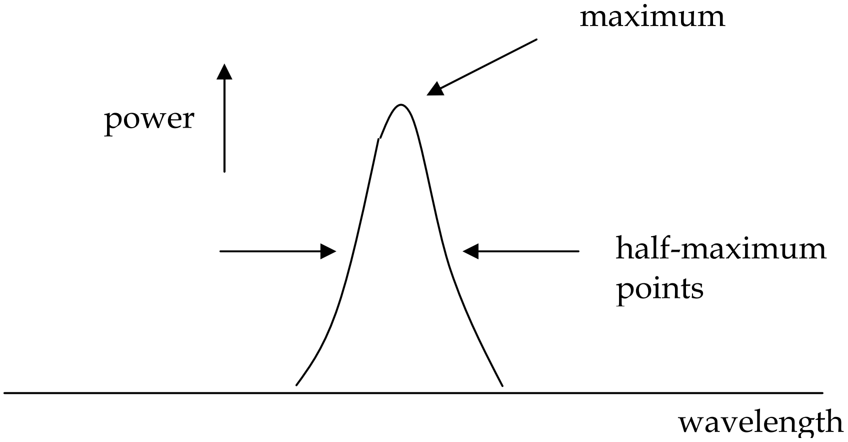


Figure 2 – Power as a function of wavelength for a typical laser beam.

Notice that the shape of the power curve has some labeled features on it. The point where the power reaches its highest value is the maximum. The maximum occurs at the center wavelength, which ideally should be the wavelength right in the middle of the spread of wavelengths contained in the power curve. You will look for the power maximum and record the center wavelength at which the maximum occurs as part of this experiment.

Notice the two arrows that point to the half-maximum points. There are two points on either side of the maximum at which the power drops to half of its maximum value; these are called the half-maximum points. You will record the power and wavelength at these half-maximum points. Then, you will subtract the two wavelength values corresponding to the half-maximum points to obtain the full-width at half-maximum (FWHM) for the laser beam. The FWHM is a measure of the wavelength width of the laser beam, measured between the half-maximum power points.

Procedure

1. The monochromator comes with several small slits which can be inserted at the entrance and exit apertures of the device - begin by removing these slits. ****Important: the dial on the monochromator that selects which wavelength will pass through it cannot be forced; if it stops turning in one direction, do not try to force it.****

2. Begin with red laser light - this should be at a wavelength of 632.8 nm (nm stands for nanometer - one billionth of a meter). Set the dial on top of the monochromator for 632.8 so that it will allow light of this wavelength to pass through it. Align the monochromator with the laser so that the red laser light is going into the monochromator and coming out the other side. Use a white piece

of paper to see if the laser beam is coming out of the monochromator – DO NOT LOOK INTO THE MONOCHROMATOR WITH YOUR EYES!

3. Align the detector with the output laser light from the monochromator. You should see a power reading on the detector scale. If you don't get a reading, try adjusting the scale on the detector until you get a reading. If it says "1." then it is overloaded and you need to turn to a less sensitive scale.

4. Slowly adjust the wavelength knob on the monochromator until the output power is at its <u>maximum</u> value. Write down the wavelength at which this happens in Table 1 on the following page. Also, make a note of the maximum power level.

5. Turn the wavelength knob so that the wavelength <u>increases</u> until the power on your detector drops to half its maximum value - record this wavelength in Table 1.

6. Now turn the wavelength knob so that the wavelength <u>decreases</u> until the power on your detector drops to half its original maximum value - record this wavelength in Table 1.

7. The difference between the wavelengths you calculated in steps 5 and 6 is called the Full Width at Half Maximum (FWHM) of the laser wavelength. What is it? Write it in Table 1.

8. Insert the 150 um slits into the entrance and exit apertures of the monochromator and repeat the above exercise, using Table 2 for your results. Did the FWHM and center wavelengths change?

9. Now switch the laser to orange (yellow, green) light and repeat the above procedure – the only difference now is, you have to determine the wavelength of the orange light. When you first switch the laser over, nothing will come out of the monochromator because the dial is set for red light. Gradually decrease the wavelength on the dial until orange light begins to appear on the exit side of the monochromator. Record the wavelength for maximum power, and then repeat the rest of the experiment. You can fill in the tables below with all your data.

Table 1 – Experimental data for monochromator using no slits.

Color	**center wavelength** (wavelength where power is maximum) **and max power, no slits**	**two wavelengths at which power is half maximum**	**FWHM , no slits** (difference between the 2wavelengths where power is half maximum)
red	wavelength:		
	power:		
orange	wavelength:		
	power:		
yellow	wavelength:		
	power:		
green	wavelength:		
	power:		

Table 2 – Experimental data for monochromator using 150 μm slits.

color	**center wavelength** (wavelength where power is maximum) **and max power, 150 μm slits**	**two wavelengths at which power is half maximum**	**FWHM , 150 μm slits** (difference between the 2wavelengths where power is half maximum)
red	wavelength:		
	power:		
orange	wavelength:		
	power:		
yellow	wavelength:		
	power:		
green	wavelength:		
	power:		

Laboratory #6: Analog Oscilloscopes

Background

An oscilloscope is an instrument which displays voltage waveforms as a function of time or frequency; the voltage level is displayed on the vertical, or "y" axis, and the time or frequency is displayed on the horizontal, or "x" axis. Oscilloscopes are used by scientists and technicians in optics, electronics, biology, and mechanical engineering, just to name a few. They are also used by auto mechanics and people who repair electrical appliances. It is essential for people in these career fields to be familiar with the use of an oscilloscope; in this lab, you will learn how to operate a simple analog oscilloscope using a function generator which will provide a periodic voltage signal to the scope. "Analog" means that the scope works with a continuous stream of voltage levels.

Procedure

In the lab, you will be given a sheet summarizing the different knobs and buttons on the oscilloscope. Your instructor will give an overview of how the scope works and will explain how you can test the function of each control on the scope. You will learn how the scope acquires and displays the voltage waveform ("triggering"), how to set the vertical scale to display the portion of the waveform you want to view ("volts per division"), how to set the horizontal scale to control how many cycles of the periodic wave you will display ("time per division"), how to read the display, how to position the waveform (vertical and horizontal position knobs), and many other functions. After you become familiar with the scope, the instructor will "mess up" the settings on your scope to see if you can get the display back the way it was originally. This will test your understanding of the controls on the analog oscilloscope.

Laboratory #7: Digital Oscilloscopes

Background

A digital oscilloscope performs the same functions as an analog oscilloscope but usually has added features. The main difference between the digital scope and the analog scope is that the digital scope converts the signals it receives into digital data, which is a discrete set of ones and zeros which represent the original voltage signal. The digital scopes you will use in this laboratory have the ability to perform automatic measurements on the voltage waveform displayed on the screen; you can press a button and find out the frequency of the signal, for example, instead of having to count boxes and multiply by a scaling factor as with the older analog scopes you used last week. The digital scope provides more analysis of the data but is also a bit harder to learn to use.

Procedure

You will be given a step-by-step tutorial which will walk you through the operation of the digital scope. This tutorial will familiarize you with the main operating features of the digital scope. You will then have the opportunity to experiment on your own to be sure you understand how the scope works.

Laboratory #8: Beam Expanders and Spatial Filters

Background

In this exercise you will learn how to use lenses in combination to make two very important optical components – a beam expander and a spatial filter. A beam expander uses two lenses to increase the diameter of a laser beam; a spatial filter does the same thing, but it also "cleans up" the beam and makes it extremely uniform in intensity across the entire diameter of the beam. This is important for holography, which is the lab we will do next week with the use of the spatial filters you will set up this week. Beam expanders are important for many applications that involve magnification, like building telescopes and microscopes.

A laser beam is usually small enough that you do not notice that the center of it is brighter than the edges. When the beam is made larger (using a beam expander), the fact that the edges are dimmer than the center becomes much more noticeable. When you want to make a hologram, you need the laser beam to completely light up the object and you need the edges of the beam that does this to be just as bright as the center of the beam. In order to make this happen, you will use a spatial filter. Let's look at how beam expanders and spatial filters work.

Beam Expander

A beam expander simply is made of two converging lenses separated by the sum of their focal lengths. If you recall the lab on combinations of lenses, this is the same way we made a simple telescope. A beam expander basically does the same thing as a telescope; it has parallel input and output rays and it provides magnification. It looks like this:

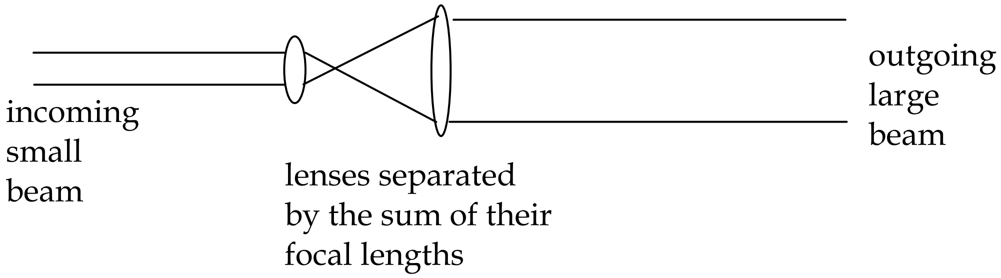


Figure 1 - Beam Expander

Spatial Filter

A spatial filter is a beam expander with one additional element: a pinhole aperture. The pinhole aperture is placed at the point where the two focal distances of the lenses meet (as shown below) and its purpose is to cut off the tails of the laser beam as it passes through. This way, when the laser beam is expanded, it will have uniform brightness across its entire diameter because the dim parts that were there before got filtered out by the pinhole.

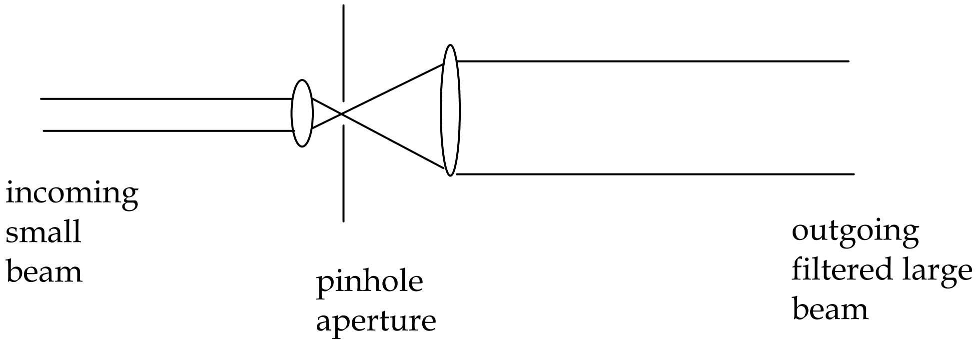


Figure 2 - Spatial Filter

The reason this works is because before the laser beam gets filtered, its intensity looks something like this:

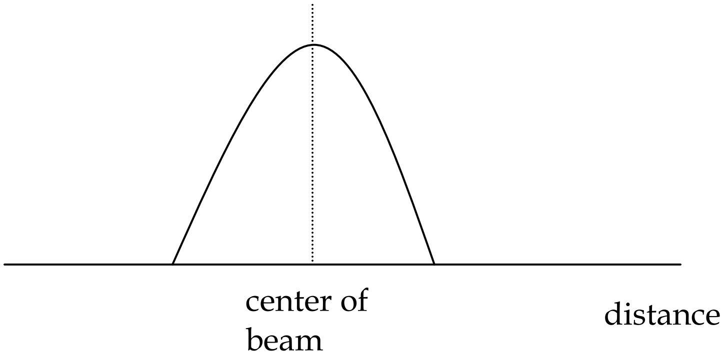


Figure 3 - Laser Beam Intensity Profile

The pinhole aperture only allows the center part of the beam to get through, so then when it gets expanded, it will not be dimmer at the edges:

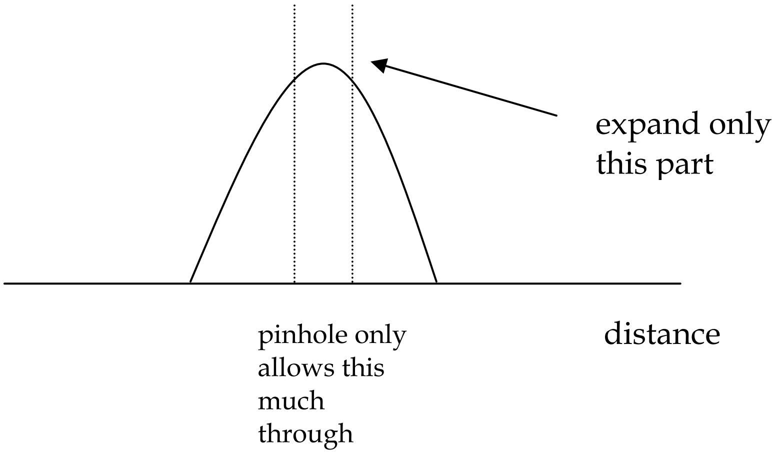


Figure 4 - Spatial filter cuts out all but the central part of the laser beam.

Procedure – Beam Expander

1. Look at the two lenses you are given – their focal lengths are carved onto the lenses themselves. Determine the separation you need to build the beam expander, and do it on the optical rail using the lens holders. Adjust the lens positions until you have a collimated beam coming out of the beam expander; **collimated means it remains the same size as it travels away from the laser**.

2. Use a ruler to estimate the size of the input beam and the output beam – determine the magnification of the beam expander by dividing the output beam size by the input beam size. Describe the quality of the beam – is it uniform, or is it brighter in the middle than it is on the edges?

3. Repeat the above steps for the second set of lenses you are given.

Procedure – Spatial Filter

1. The spatial filter assembly is already in the laser beam path – start by increasing the distance between the pinhole and the lens. The distance should be longer than the focal length of the objective.

2. Adjust the vertical and horizontal screws until the light coming through is maximized.

3. Move the lens a little closer to the pinhole and again maximize the light intensity using the vertical and horizontal screws.

4. Repeat this procedure until you have an intense, round, uniform laser beam emerging.**This takes time and patience – don't expect this to happen in 5 minutes!

****IMPORTANT – As the distance between the components gets very small be careful not to make them collide! This will break the lens.**

Laboratory #9: Holography

Background

Holography is the process of using a laser to record a three-dimensional image of an object on a holographic plate. In order to understand how this works, we need to first discuss the idea of interference, which is what happens when two or more light waves meet at the same point in space. Picture light waves as sine waves which travel through space, like this:

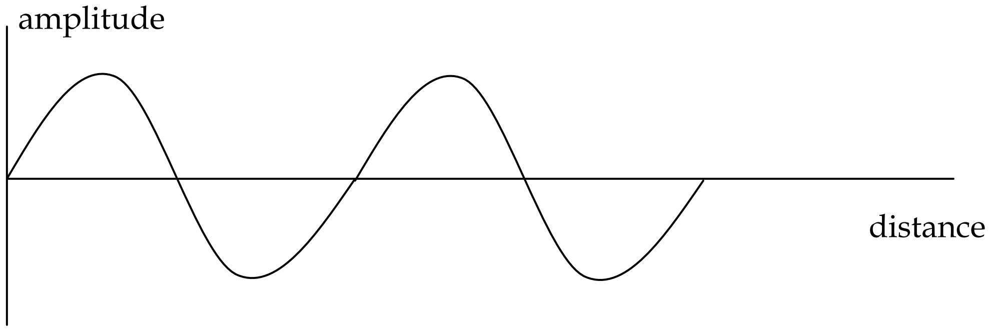


Figure 1 – An example of a light wave.

Let's say that two such waves meet at some point in space. What happens to them? They simply add together. If you have two waves that meet, you add their amplitudes, point-by-point, at each point in space where they meet to form what is called a resultant wave. Now, this resultant wave can end up being larger than either of the two separate waves, or it can be smaller than either of the two separate waves. Which way it ends up depends on the relative phases of the two waves when they meet. Phase refers to which part of the wave we are looking at in a particular point in space, and we usually speak of the phase of one wave compared to another. For example, the two waves shown in Figure 2 have a phase difference of 180 degrees:

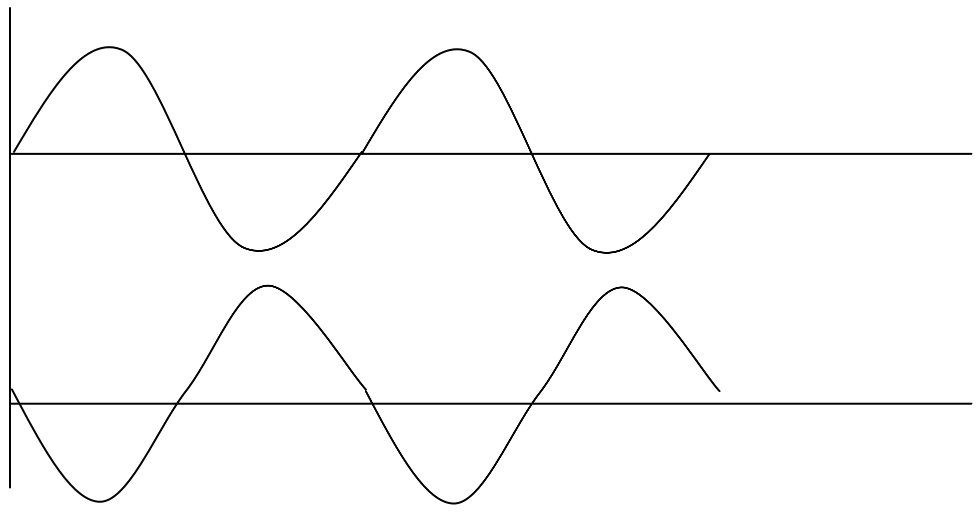


Figure 2 - Two waves which have a phase difference of 180 degrees.

As you can see, a 180 degree phase difference means that the waves are exact opposites of one another: the crests of one line up with the valleys of the other. This is called "180 degrees out of phase." This means that if we were to add them together, they would completely cancel each other out. This is called destructive interference.

Now, if two waves have no phase difference between them, we say that they are "in phase," which means that the crests and valleys of the two waves line up perfectly. If we add two in-phase waves together, we get a resultant wave that is larger than either of the two separate waves; this is called constructive interference. If the two waves line up in any way other than exactly in phase or 180 degrees "out of phase," we get a more complicated wave pattern, but it is still called interference.

The next thing you need to know to understand holograms is that laser light is coherent. This is what makes it so powerful and dangerous! Coherence means that all of the light waves in a laser beam travel together with the same phase, meaning that they have constructive interference and none of the power gets wasted. In an ordinary light bulb, the waves do not travel together with the same phase; all the light waves from a light bulb have different phases and they vary randomly, which means that many of them have destructive interference and power is wasted. This is why a few milliwatts from a laser can blind you but a 60 watt light bulb can be looked at briefly without irritating your eyes.

Because a laser beam is coherent, it can tell how far it has traveled – that is something unique to laser light and it is what makes holograms, CD players, and DVD players work, to name a few. A laser beam can tell how far it has traveled because the phase does not randomly vary, which means that we can split the laser beam in two and keep one beam as a "reference beam" and use the other to send out to bounce off of an object and come back (the "object beam"). When the object beam comes back, we compare it to the reference beam, and <u>the difference in phase between the object and reference beams will tell us exactly how far the object beam has traveled</u>.

Why? Because phase difference is related to wavelength, and we know the wavelength of the light we are using. Wavelength is the physical length of one cycle of a wave (the length of the smallest repeatable unit of the wave); Figure 2 shows two cycles, or two wavelengths, of each wave. For example, look at Figure 2 – can you tell that the top wave is just like the bottom wave shifted by half the wavelength of the wave? That's what it means when two waves are 180 degrees out of phase with one another – it means that one of them is shifted a half-wavelength compared to the other one.

Let's look at the following example: 1) start with two waves that are in phase, use one as a reference and use the other to bounce off of an object; 2) after the waves are recombined, they have a 180-degree phase difference; 3) this means that the one that went out to the object traveled a half-wavelength more or less than the reference beam in the same amount of time; 4) therefore, the two beams, when compared to one another, ended up shifted by a half-wavelength.

So, a 180 degree phase difference corresponds to a half-wavelength in distance units. Different distances to the object will correspond to different phase differences between the object and reference beams. For example, a 90-degree phase difference corresponds to a quarter-wavelength, and 360 degrees corresponds to a full wavelength. (You should be able to see the relationship between phase and wavelength from these examples.) These phase differences are recorded in an interference pattern on a holographic plate; the interference pattern is simply the addition of the object and reference waves at each point in space where they meet. The phase information (which is actually distance information) is contained within the interference pattern itself because the phase differences between the waves determine what the interference pattern looks like. For example, the interference pattern will contain spots of constructive interference when the object and reference waves are in phase, or destructive interference when the object and reference waves are 180 degrees out of phase. For all other phase differences corresponding to different distances to features on the object (ranging from 0 to 360 degrees), the interference pattern is more complicated-looking, but it still gets recorded on the holographic plate. So, this is why a hologram contains both distance (depth) information as well as brightness information from the object, and therefore looks three-dimensional. Regular pictures do not look three-dimensional because they only contain the brightness information and no depth information. This is because a regular camera looking at light that is not coherent has no way to record phase information, which is what tells us about distance.

Figure 3 shows a simple set-up for recording a hologram, which is what you will do in this week's lab exercise. The reference beam is simply the expanded and filtered laser beam as it hits the transparent holographic plate; the object beam is the part of the laser beam that bounces off of the object and is reflected back towards the holographic plate. When the reference and object beams meet, an interference pattern is formed that is recorded on the holographic plate. This plate must then be developed using a method similar, but not identical, to the method used to develop regular 35 mm camera film. The details on how to develop the plates will be given in class when we make the holograms.

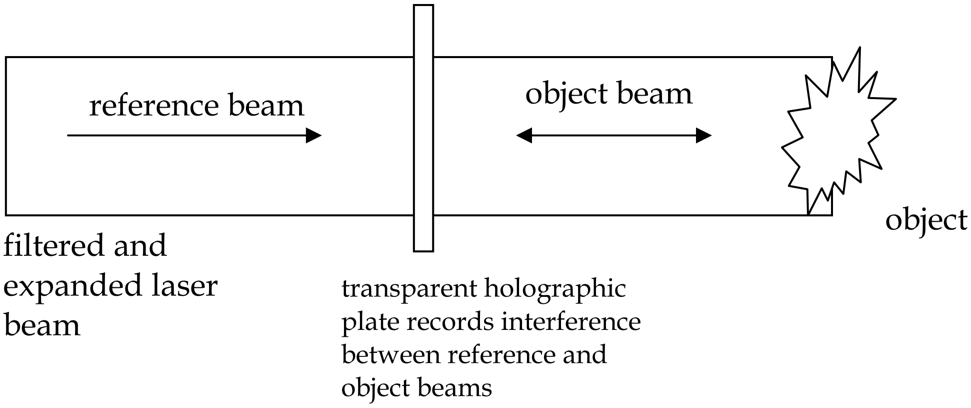


Figure 3 – Set-up for recording holograms.

To view the holograms that we will make in class, an ordinary white light bulb can be used, but the holograms will look even better if they are viewed with the same laser set-up used to record them. In class, we will attempt to view the holograms we make both with a bright filtered light bulb (holding the hologram in front of the bulb and looking down through the plate to try to see the image) and with the laser set-up. To view the hologram with the laser set-up, the plate should be placed back on the stand where it was recorded and you should look through the plate (away from the laser, not towards it!) to view the image, which should look very three-dimensional and like it is sitting behind the plate.

Note that when you look at the holographic plate itself, you don't see the image; it is not like looking at a photo. The plate only contains the interference pattern; the image from the plate is seen "floating" behind the plate when it has light hitting it and you look at the right angle.

Procedure for Recording the Hologram

1. Your lab bench will be set up with a filtered, expanded laser beam ready to use when you arrive. Do not make any adjustments to the spatial filter assembly;

2. Select an object of yours to use to make the hologram; things that work well include keys, coins, and jewelry;

3. Place the object in the clip provided and set it about two inches behind the clip which will hold the holographic plate. Set the object at a slight angle compared to the way the plate will stand (instructor will help);

4. Make sure all obstacles in the room are cleared out of the way before the experiment begins; make sure the laser beam is covered and all lights in the room are off ;

5. One student form each lab group will come to the front lab bench where the instructor will give you the holographic plate. You can use the green-filtered flashlights to see where you are going, but try to avoid shining the light directly on the plate;

6. Place the plate in the clip and set it on the stand in front of your object. The instructor will come around and make sure the plate placement is correct;

7. When everyone is ready, the instructor will say “go” and you will unblock the laser beam and expose the holographic plate for 2 – 3 seconds. The instructor will say “stop” when it is time to block the laser again;

8. Students will then develop the plates using the step-by-step instructions given in the lab. All but the last step must be done in darkness except for indirect green light from the flashlights, so be careful about moving around. Handle the plates with the tongs, by the edges, and try not touch them or clang them around in the beakers too much;

9. After development, we will view the holograms and then repeat the experiment.

Laboratory #10: High-Power Laser Demonstration

This last laboratory for the lasers and optics portion of the course will consist of a demonstration of some of the different high-power lasers available in the QCC Physics Department. The first laser we will demonstrate is a carbon-dioxide laser capable of emitting approximately 10 Watts of power. This laser emits radiation with a wavelength of 10.6 μm, which is in the infrared portion of the electromagnetic spectrum; human eyes cannot see infrared radiation, so the extremely powerful "light" that comes out of this laser will be invisible to you. You will need to wear protective goggles when this laser is on. The beams from the lasers we will be demonstrating are invisible but they can damage your eyes if you are not wearing eye protection, so once these lasers are turned on, do not take off your goggles for any reason. We will demonstrate this laser cutting very precise and clean-edged holes in styrofoam. Carbon-dioxide lasers are used in industry for cutting, drilling, and marking anything from wood to metal. They can make cleaner and more precise holes and marks than can mechanical drilling equipment.

The second laser we will demonstrate is called a neodymium-YAG laser, where YAG stands for yittrium-aluminum-garnet and is a type of glass. If you looked at the inside of this laser where the energy source is, the Nd:YAG "rod" would look like a very clear, polished piece of glass. This laser is capable of emitting 40 Watts of continuous power, or 10 Watts (average) of concentrated pulsed power. Even though the average power for the pulses is lower than the continuous power, the pulses are very dangerous because they concentrate that power into very short bursts with high peak powers. This laser emits at a wavelength of 1.06 μm, which is also in the infrared (invisible) portion of the spectrum. You will need to wear a different pair of goggles for this laser demonstration; goggles are designed to protect your eyes from very specific wavelengths and you can’t use just one pair of goggles for all kinds of different lasers. The YAG laser will be used to burn a hole in a piece of wood, and you will see how fast this happens and how clean the edges of the burned area are. A laser like this is also used for drilling, machining, and for laser artwork! This laser is designed so that a special crystal can be installed, called a “frequency-doubling crystal,” which will turn the 1.06 μm light into 532 nm light, which is green. When you do this, you lose about half (or more) of the power, but it is still a very powerful beam.