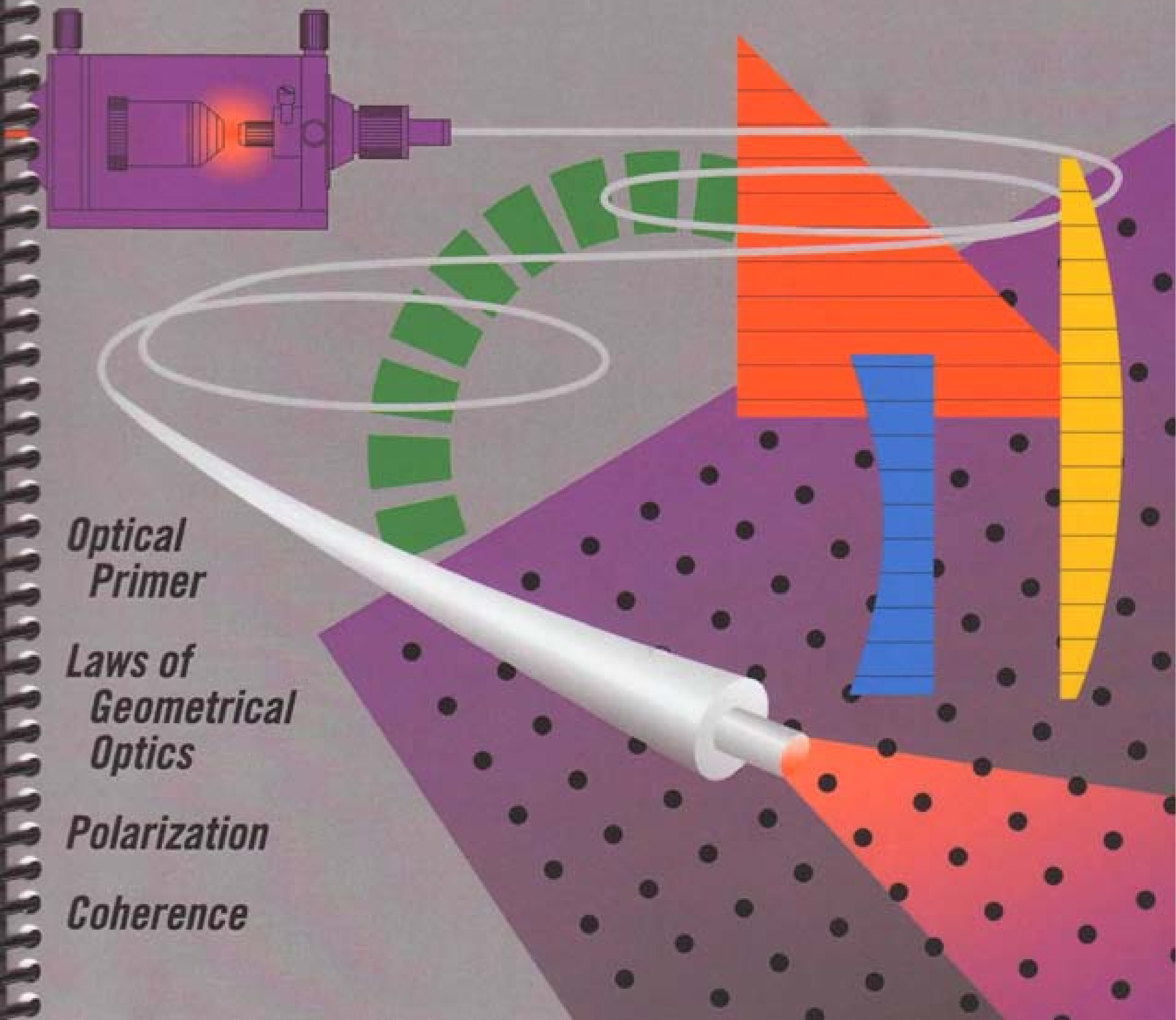
Newport

Projects in Optics Workbook



Optical Primer

Laws of Geometrical Optics

Polarization

Coherence

Projects in Optics

Applications Workbook

Created by the technical staff of Newport Corporation
with the assistance of Dr. Donald C. O'Shea of the School of Physics
at the Georgia Institute of Technology.

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Projects In Optics

Preface

The Projects in Optics Kit is a set of laboratory equipment containing all of the optics and optomechanical components needed to complete a series of experiments that will provide students with a basic background in optics and practical hands-on experience in laboratory techniques. The projects cover a wide range of topics from basic lens theory through interferometry and the theory of imaging. The Project in Optics Handbook has been developed by the technical staff of Newport Corporation and Prof. D. C. O'Shea, in order to provide educators with a convenient means of stimulating their students' interest and creativity.

This handbook begins with a description of several mechanical assemblies that will be used in various combinations for each experiment. In addition, these components can be assembled in many other configurations that will allow more complex experiments to be designed and executed. One of the benefits from constructing these experiments using an optical bench (sometimes called an optical breadboard) plus standard components, is that the student can see that the components are used in a variety of different circumstances to solve the particular experimental problem, rather than being presented with an item that will perform only one task in one way.

A short Optics Primer relates a number of optical phenomena to the ten projects in this handbook. Each project description contains a statement of purpose that outlines the phenomena to be measured, the optical principle is being studied, a brief look at the relevant equations governing the experiment or references to the appropriate section of the Primer, a list of all necessary equipment, and a complete step-by-step instruction set which will to guide the student through the laboratory exercise. After the detailed experiment description is a list of somewhat more elaborate experiments that will extend the basic concepts explored in the experiment. The ease with which these additional experiments can be done will depend both on the resources at hand and the inventiveness of the instructor and the student.

The equipment list for the individual experiments is given in terms of the components assemblies, plus items that are part of the project kits. There are a certain number of required items that are to be supplied by the instructor. Items such as metersticks and tape measures are easily obtainable. Others, for the elaborate experiments, may be somewhat more difficult, but many are found in most undergraduate programs. Note that along with lasers and adjustable mirror mounts, index cards and tape is used to acquire the data. The student should understand that the purpose of the equipment is get reliable data, using whatever is required. The student should be allowed some ingenuity in solving some of the problems, but if his or her choices will materially affect their data an instructor should be prepared to intervene.

These experiments are intended to be used by instructors at the sophomore/junior level for college engineering and physical science students or in an advanced high school physics laboratory course. The projects follow the general study outline found in most optical text books, although some of the material on lasers and imaging departs from the standard curriculum at the present time. They should find their greatest applicability as instructional aids to reinforcing the concepts taught in these texts.

Acknowledgement: A large part of the text and many of the figures of "An Optics Primer" are based on Chapter One of *Elements of Modern Optical Design* by Donald C. O'Shea, published by J. Wiley and Sons, Inc., New York ©1985. They are reprinted with permission of John Wiley & Sons, Inc.

0.0 An Optics Primer

The field of optics is a fascinating area of study. In many areas of science and engineering, the understanding of the concepts and effects in that field can be difficult because the results are not easy to display. But in optics, you can see exactly what is happening and you can vary the conditions and see the results. This primer is intended to provide an introduction to the 10 optics demonstrations and projects contained in this **Projects in Optics** manual. A list of references that can provide additional background is given at the end of this primer.

0.1 Geometrical Optics

There is no need to convince anyone that light travels in straight lines. When we see rays of sunlight pouring between the leaves of a tree in a light morning fog, we trust our sight. The idea of light rays traveling in straight lines through space is accurate as long as the wavelength of the radiation is much smaller than the windows, passages, and holes that can restrict the path of the light. When this is not true, the phenomenon of diffraction must be considered, and its effect upon the direction and pattern of the radiation must be calculated. However, to a first approximation, when diffraction can be ignored, we can consider that the progress of light through an optical system may be traced by following the straight line paths or rays of light through the system. This is the domain of geometrical optics.

Part of the beauty of optics, as it is for any good game, is that the rules are so simple, yet the consequences so varied and, at times, elaborate, that one never tires of playing. Geometrical optics can be expressed as a set of three laws:

1. **The Law of Transmission.**

   In a region of constant refractive index, light travels in a straight line.

2. **Law of Reflection.**

   Light incident on a plane surface at an angle θ_i with respect to the normal to the surface is reflected through an angle θ_r equal to the incident angle (**Fig. 0.1**).

$$\theta_i = \theta_r \tag{0.1}$$

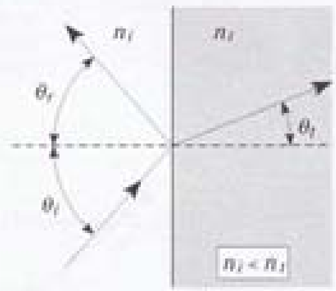


Figure 0.1 Reflection and refraction of light at an interface.

3. **Law of Refraction (Snell's Law).**

Light in a medium of refractive index n_i incident on a plane surface at an angle θ_i with respect to the normal is refracted at an angle θ_t in a medium of refractive index n_t as (**Fig. 0.1**).

$$n_i \sin\theta_i = n_t \sin\theta_t \qquad (0\text{-}2)$$

A corollary to these three rules is that the incident, reflected, and transmitted rays, and the normal to the interface all lie in the same plane, called the **plane of incidence**, which is defined as the plane containing the surface normal and the direction of the incident ray.

Note that the third of these equations is not written as a ratio of sines, as you may have seen it from your earlier studies, but rather as a product of $n \sin\theta$. This is because the equation is unambiguous as to which refractive index corresponds to which angle. If you remember it in this form, you will never have any difficulty trying to determine which index goes where in solving for angles. **Project #1** will permit you to verify the laws of reflection and refraction.

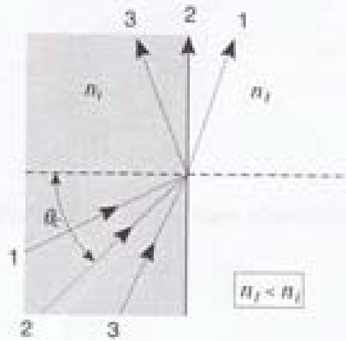


Figure 0.2. Three rays incident at angles near or at the critical angle.

A special case must be considered if the refractive index of the incident medium is greater than that of the transmitting medium, $(n_i > n_t)$. Solving for θ_t, we get

$$\sin\theta_t = (n_i / n_t) \sin\theta_i \qquad (0\text{-}3)$$

In this case, $n_i / n_t > 1$, and $\sin\theta_i$ can range from 0 to 1. Thus, for large angles of θ_i it would seem that we could have $\sin\theta_t > 1$. But $\sin\theta_t$ must also be less than one, so there is a **critical angle** $\theta_i = \theta_c$, where $\sin\theta_c = n_t / n_i$ and $\sin\theta_t = 1$. This means the transmitted ray is traveling perpendicular to the normal (i.e., parallel to the interface), as shown by ray #2 in **Fig. 0.2**. For incident angles θ_i greater than θ_c no light is transmitted. Instead the light is totally reflected back into the incident medium (see ray #3, **Fig. 0.2**). This effect is called **total internal reflection** and will be used in **Project #1** to measure the refractive index of a prism.

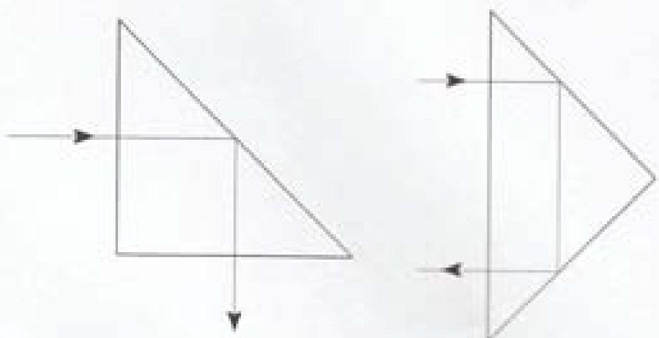


Figure 0.3. Total internal reflection from prisms.

As illustrated in **Fig. 0.3**, prisms can provide highly reflecting non-absorbing mirrors by exploiting total internal reflection.

Total internal reflection is the basis for the transmission of light through many optical fibers. We do not cover the design of optical fiber systems in this manual because the application has become highly specialized and more closely linked with modern communications theory than geometrical optics. A separate manual and series of experiments on fiber optics is available from Newport in our **Projects in Fiber Optics**.

0.1.1. Lenses

In most optical designs, the imaging components — the lenses and curved mirrors — are symmetric about a line, called the **optical axis**. The curved surfaces of a lens each have a center of curvature. A line drawn between the centers of curvatures of the two surfaces of the lens establishes the optical axis of the lens, as shown in **Fig.0.4**. In most cases, it is assumed that the optical axes of all components are the same. This line establishes a reference line for the optical system.

By drawing rays through a series of lenses, one can determine how and where images occur. There are conventions for tracing rays; although not universally accepted, these conventions have sufficient usage that it is convenient to adopt them for sketches and calculations.

1. An object is placed to the left of the optical system. Light is traced through the system from left to right until a reflective component alters the general direction.

   Although one could draw some recognizable object to be imaged by the system, the simplest object is a vertical arrow. (The arrow, imaged by the optical system, indicates if subsequent images are erect or inverted with respect to the original object and other images.) If we assume light from the object is sent in all directions, we can draw a sunburst of rays from any point on the arrow. An image is formed where all the rays from the point, that are redirected by the optical system, again converge to a point.

   A positive lens is one of the simplest image-forming devices. If the object is placed very far away ("at infinity" is the usual term), the rays from the object are parallel to the optic axis and produce an image at the focal point of the lens, a distance f from the lens (the distance f is the **focal length** of the lens), as shown in **Fig. 0.5(a)**. A negative lens also has a focal point, as shown in **Fig. 0.5(b)**. However, in this case, the parallel rays do not converge to a point, but instead appear to diverge from a point a distance f in front of the lens.

2. A light ray parallel to the optic axis of a lens will pass, after refraction, through the focal point, a distance f from the vertex of the lens.

3. Light rays which pass through the focal point of a lens will be refracted parallel to the optic axis.

4. A light ray directed through the center of the lens is undeviated.

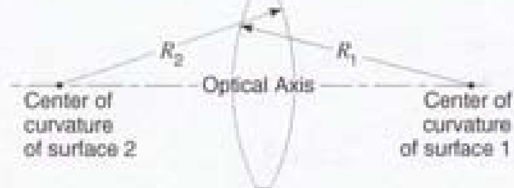
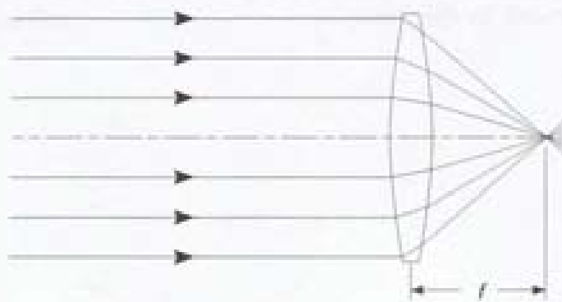
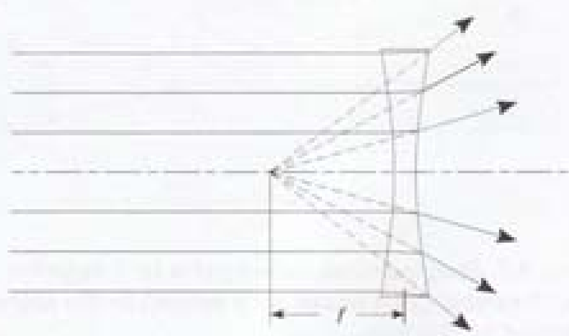


Figure 0.4 Optical axis of a lens.



a.



b.

Figure 0.5. Focusing of parallel light by positive and negative lenses.

The formation of an image by a positive lens is shown in **Fig. 0.6**. Notice that the rays cross at a point in space. If you were to put a screen at that point you would see the image in focus there. Because the image can be found at an accessible plane in space, it is called a **real image**. For a negative lens, the rays from an object do not cross after transmission, as shown in **Fig. 0.7**, but appear to come from some point behind the lens. This image, which cannot be observed on a screen at some point in space, is called a **virtual image**. Another example of a virtual image is the image you see in the bathroom mirror in the morning. One can also produce a virtual image with a positive lens, if the object is located between the vertex and focal point. The labels, "real" and "virtual", do not imply that one type of image is useful and the other is not. They simply indicate whether or not the rays redirected by the optical system actually cross.

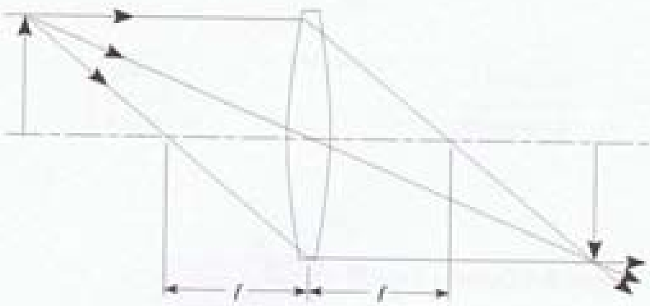


Figure 0.6. Imaging of an object point by a positive lens. A real inverted image with respect to the object is formed by the lens.

Most optical systems contain more than one lens or mirror. Combinations of elements are not difficult to handle according to the following rule:

5. The image of the original object produced by the first element becomes the object for the second element. The object of each additional element is the image from the previous element.

More elaborate systems can be handled in a similar manner. In many cases the elaborate systems can be broken down into simpler systems that can be handled separately, at first, then joined together later.

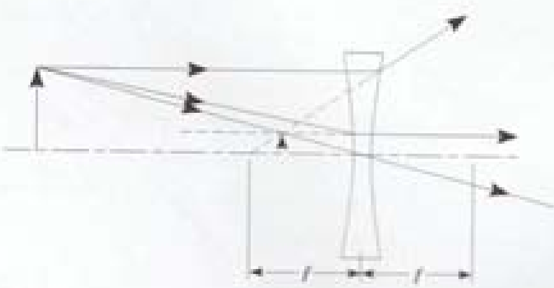


Figure 0.7. Imaging of an object point by a negative lens. A virtual erect image with respect to the object is formed by the lens.

0.2 Thin Lens Equation

Thus far we have not put any numbers with the examples we have shown. While there are graphical methods for assessing an optical system, sketching rays is only used as a design shorthand. It is through calculation that we can determine if the system will do what we want it to. And it is only through these calculations that we can specify the necessary components, modify the initial values, and understand the limitations of the design.

Rays traced close to the optical axis of a system, those that have a small angle with respect to the axis, are most easily calculated because some simple approximations can be made in this region. This approximation is called the **paraxial approximation**, and the rays are called **paraxial rays**.

Before proceeding, a set of sign conventions should be set down for the thin lens calculations to be considered next. The conventions used here are those used in most high school and college physics texts. They are not the conventions used by most optical engineers. This is unfortunate, but it is one of the difficulties that is found in many fields of technology. We use a standard right-handed coordinate system with light propagating generally along the *z*-axis.

1. Light initially travels from left to right in a positive direction.
2. Focal lengths of converging elements are positive; diverging elements have negative focal lengths.
3. Object distances are positive if the object is located to the left of a lens and negative if located to the right of a lens.
4. Image distances are positive if the image is found to the right of a lens and negative if located to the left of a lens.

We can derive the object-image relationship for a lens. With reference to **Fig. 0.8** let us use two rays from an off-axis object point, one parallel to the axis, and one through the front focal point. When the rays are traced, they form a set of similar triangles *ABC* and *BCD*. In ABC,

$$\frac{h_o + h_i}{s_o} = \frac{h_i}{f} \qquad \text{(0-4a)}$$

and in BCD

$$\frac{h_o + h_i}{s_i} = \frac{h_o}{f} \qquad \text{(0-4b)}$$

Adding these two equations and dividing through by $h_o + h_i$ we obtain the **thin lens equation**

$$\frac{1}{f} = \frac{1}{s_i} + \frac{1}{s_o} \qquad \text{(0-5)}$$

Solving equations 0-4a and 0-4b for $h_o + h_i$, you can show that the **transverse magnification** or lateral magnification, *M*, of a thin lens, the ratio of the image height h_i to the object height h_o, is simply the ratio of the image distance over the object distance:

$$M = \frac{h_i}{h_o} = \frac{-s_i}{s_o} \qquad \text{(0-6)}$$

With the inclusion of the negative sign in the equation, not only does this ratio give the size of the final image, its sign also indicates the orientation of the image

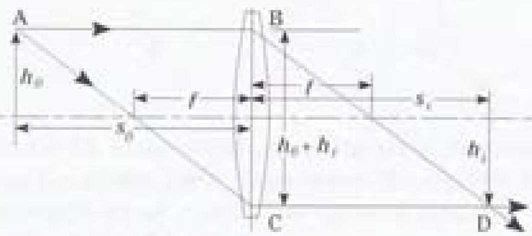


Figure 0.8. Geometry for a derivation of the thin lens equation.

relative to the object. A negative sign indicates that the image is inverted with respect to the object. The axial or longitudinal magnification, the magnification of a distance between two points on the axis, can be shown to be the square of the lateral or transverse magnification.

$$M_l = M^2 \tag{0-7}$$

In referring to transverse magnification, an unsubscripted M will be used.

The relationship of an image to an object for a positive focal length lens is the same for all lenses. If we start with an object at infinity we find from **Eq. 0-5** that for a positive lens a real image is located at the focal point of the lens ($1/s_o = 0$, therefore $s_i = f$), and as the object approaches the lens the image distance increases until it reaches a point $2f$ on the other side of the lens. At this point the object and images are the same size and the same distance from the lens. As the object is moved from $2f$ to f, the image moves from $2f$ to infinity. An object placed between a positive lens and its focal point forms a virtual, magnified image that decreases in magnification as the object approaches the lens. For a negative lens, the situation is simpler: starting with an object at infinity, a virtual image, demagnified, appears to be at the focal point on the same side of the lens as the object. As the object moves closer to the lens so does the image, until the image and object are equal in size at the lens. These relationships will be explored in detail in **Project #2**.

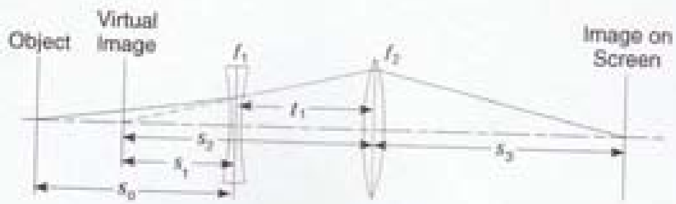


Figure 0.9 Determination of the focal length of a negative lens with the use of a positive lens of known focal length.

The calculation for a combination of lenses is not much harder than that for a single lens. As indicated earlier with ray sketching, the image of the preceding lens becomes the object of the succeeding lens.

One particular situation that is analyzed in **Project #2** is determining the focal length of a negative lens. The idea is to refocus the virtual image created by the negative lens with a positive lens to create a real image. In **Fig. 0.9** a virtual image created by a negative lens of unknown focal length f_1 is reimaged by a positive lens of known focal length f_2. The power of the positive lens is sufficient to create a real image at a distance s_3 from it. By determining what the object distance s_2 should be for this focal length and image distance, the location of the image distance for the negative lens can be found based upon rule 5 in Sec. 0.1: the image of one lens serves as the object for a succeeding lens. The image distance s_1 for the negative lens is the separation between lenses t_1 minus the object distance s_2 of the positive lens. Since the original object distance s_0 and the image distance s_1 have been found, the focal length of the negative lens can be found from the thin lens equation.

In many optical designs several lenses are used together to produce an improved image. The effective focal length of the combination of lenses can be calculated by ray tracing methods. In the case of two thin lenses in contact, the effective focal length of the combination is given by

$$\frac{1}{f}=\frac{1}{f_1}+\frac{1}{f_2} \qquad (0\text{-}8)$$

0.3 Diffraction

Although the previous two sections treated light as rays propagating in straight lines, this picture does not fully describe the range of optical phenomena that can be investigated within the experiments in **Projects in Optics**. There are a number of additional concepts that are needed to explain certain limitations of ray optics and to describe some of the techniques that allow us to analyze images and control the amplitude and direction of light. This section is a brief review of two important phenomena in physical optics, interference and diffraction. For a complete discussion of these and related subjects, the reader should consult one or more of the references.

0.3.1 Huygen's Principle

Light is an electromagnetic wave made up of many different wavelengths. Since light from any source (even a laser!) consists of fields of different wavelength, it would seem that it would be difficult to analyze their resultant effect. But the effects of light made up of many colors can be understood by determining what happens for a monochromatic wave (one of a single wavelength) then adding the fields of all the colors present. Thus by analysis of these effects for monochromatic light, we are able to calculate what would happen in non-monochromatic cases. Although it is possible to express an electromagnetic wave mathematically, we will describe light waves graphically and then use these graphic depictions to provide insight to several optical phenomena. In many cases it is all that is needed to get going.

An electromagnetic field can be pictured as a combination of electric (*E*) and magnetic (*H*) fields whose directions are perpendicular to the direction of propagation of the wave (*k*), as shown in **Fig. 0.10**. Because the electric and magnetic fields are proportional to each other, only one of the fields need to be described to understand what is happening in a light wave. In

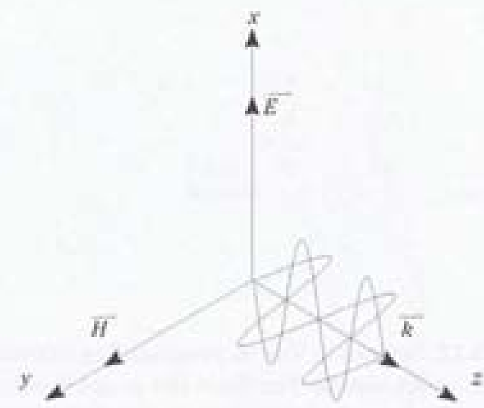


Figure 0.10. Monochromatic plane wave propagating along the z axis. For a plane wave, the electric field is constant in an x-y plane. The vector k is in the direction of propagation.

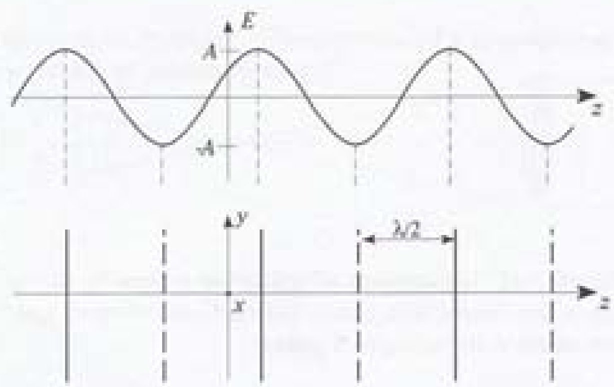


Figure 0.11. Monochromatic plane wave propagating along the z-axis. For a plane wave, the electric field is constant in an x-y plane. The solid lines and dashed lines indicate maximum positive and negative field amplitudes.

most cases, a light wave is described in terms of the electric field. The diagram in **Fig 0.10** represents the field at one point in space and time. It is the arrangement of the electric and magnetic fields in space that determines how the light field progresses.

One way of thinking about light fields is to use the concept of wavefront. If we plot the electric fields as a function of time along the direction of propagation, there are places on the wave where the field is a maximum in one direction and other places where it is zero, and other places where the field is a maximum in the opposite direction, as shown in **Fig. 0.11**. These represent different **phases** of the wave. Of course, the phase of the wave changes continuously along the direction of propagation. To follow the progress of a wave, however, we will concentrate on one particular point on the phase, usually at a point where the electric field amplitude is a maximum. If all the points in the neighborhood have this same amplitude, they form a surface of constant phase, or **wavefront**. In general, the wavefronts from a light source can have any shape, but some of the simpler wavefront shapes are of use in describing a number of optical phenomena.

A **plane wave** is a light field made up of plane surfaces of constant phase perpendicular to the direction of propagation. In the direction of propagation, the electric field varies sinusoidally such that it repeats every wavelength. To represent this wave, we have drawn the planes of maximum electric field strength, as shown in **Fig. 0.11**, where the solid lines represent planes in which the electric field vector is pointing in the positive y-direction and the dashed lines represent plane in which the electric field vector is pointing in the negative y-direction. The solid planes are separated by one wavelength, as are the dashed planes.

Another useful waveform for the analysis of light waves is the spherical wave. A **point source**, a fictitious source of infinitely small dimensions, emits a wavefront that travels outward in all directions producing wavefronts consisting of spherical shells centered about the point source. These **spherical waves** propagate outward from the point source with radii equal to the distance between the wavefront and the point source, as shown schematically in **Fig. 0.12**. Far away from the point source, the radius of the wavefront is so large that the wavefronts approximate plane waves. Another way to create spherical waves is to focus a plane wave. **Figure 0.13** shows the spherical waves collapsing to a point and then expanding. The waves never collapse to a true point because of diffraction (next Section). There are many other possible forms of wave fields, but these two are all that is needed for our discussion of interference.

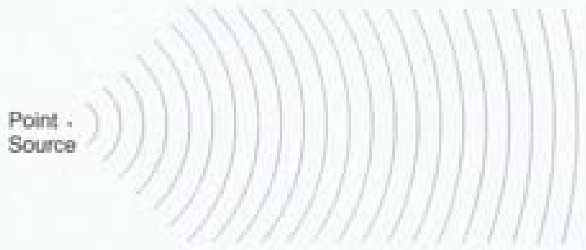


Figure 0.12. Spherical waves propagating outward from the point source. Far from the point source, the radius of the wavefront is large and the wavefronts approximate plane waves.

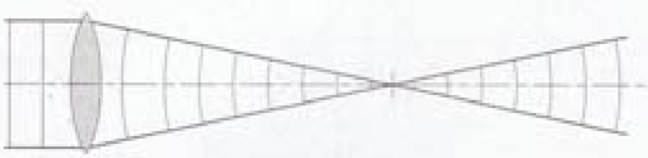


Figure 0.13. Generation of spherical waves by focusing plane waves to a point. Diffraction prevents the waves from focusing to a point.

What we have described are single wavefronts. What happens when two or more wavefronts are present in the same region? Electromagnetic theory shows that we can apply the **principle of superposition**: where waves overlap in the same region of space, the resultant field at that point in space and time is found by adding the electric fields of the individual waves at a point. For the present we are assuming that the electric fields of all the waves have the same polarization (direction of the electric field) and they can be added as scalars. If the directions of the fields are not the same, then the fields must be added as vectors. Neither our eyes nor any light detector "sees" the electric field of a light wave. All detectors measure the **square** of the time averaged electric field over some area. This is the **irradiance** of the light given in terms of watts/square meter (w/m^2) or similar units of power per unit area.

Given some resultant wavefront in space, how do we predict its behavior as it propagates? This is done by invoking **Huygen's Principle**. Or, in terms of the graphical descriptions we have just defined, Huygen's Construction (see **Fig. 0.14**): Given a wavefront of arbitrary shape, locate an array of point sources on the wavefront, so that the strength of each point source is proportional to the amplitude of the wave at that point. Allow the point sources to propagate for a time t, so that their radii are equal to ct (c is the speed of light) and add the resulting sources. The resultant envelope of the point sources is the wavefront at a time t after the initial wavefront. This principle can be used to analyze wave phenomena of considerable complexity.

0.3.2 Fresnel and Fraunhofer Diffraction

Diffraction of light arises from the effects of apertures and interface boundaries on the propagation of light. In its simplest form, edges of lenses, apertures, and other optical components cause the light passing through the optical system to be directed out of the paths indicated by ray optics. While certain diffraction effects prove useful, ultimately all optical performance is limited by diffraction, if there is sufficient signal, and by electrical or optical "noise", if the signal is small.

When a plane wave illuminates a slit, the resulting wave pattern that passes the slit can be constructed using Huygens' Principle by representing the wavefront in the slit as a collection of point sources all emitting in phase. The form of the irradiance pattern that is observed depends on the distance from the diffraction aperture, the size of the aperture and the wavelength of the illumination. If the diffracted light is examined close to the aperture, the pattern will resemble the aperture with a few surprising variations (such as finding a point

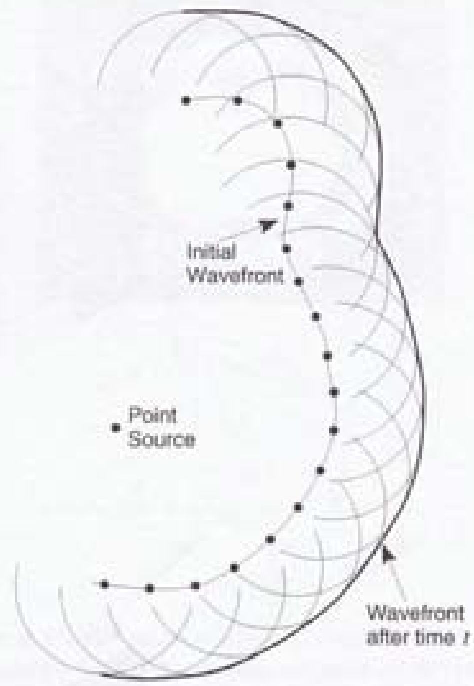


Figure. 0.14. Huygen's Construction of a propagating wavefront of arbitrary shape.

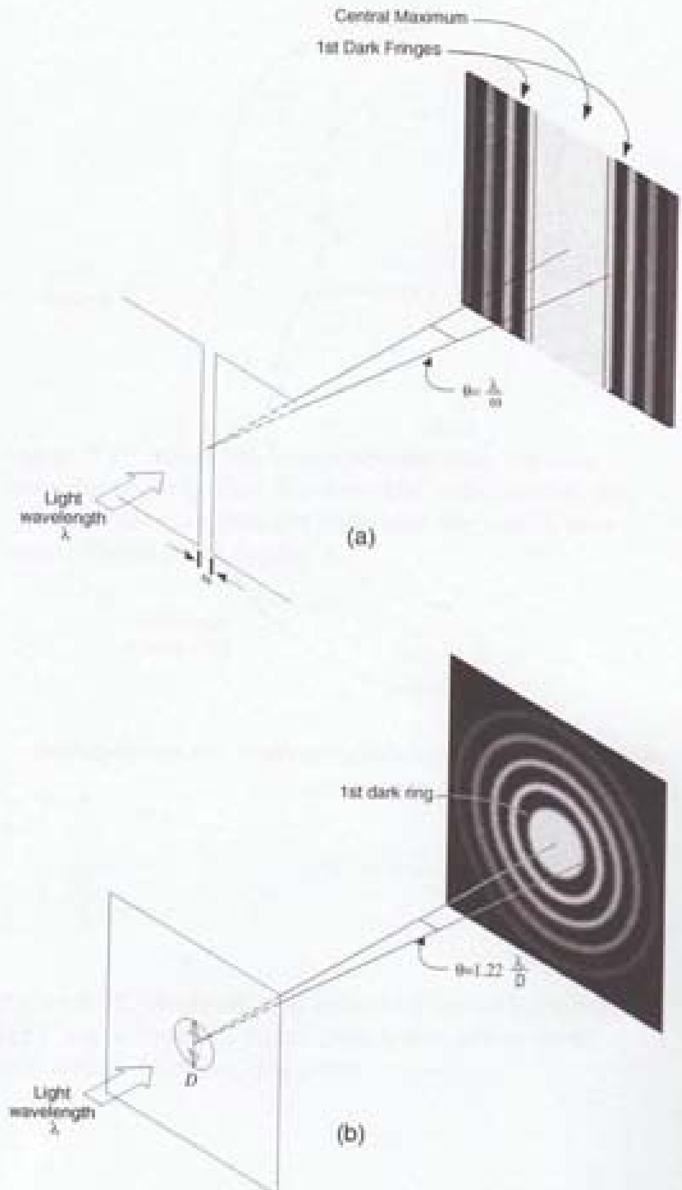


Figure 0.15. Diffraction of light by apertures. (a) Single slit. (b) Circular aperture.

of light in the shadow of circular mask!). This form of diffraction is called **Fresnel** (Freh-nell) **diffraction** and is somewhat difficult to calculate.

At a distance from the aperture the pattern changes into a **Fraunhofer diffraction** pattern. This type of diffraction is easy to calculate and determines in most cases, the optical limitations of most precision optical systems. The simplest diffraction pattern is that due to a long slit aperture. Because of the length of the slit relative to its width, the strongest effect is that due to the narrowest width. The resulting diffraction pattern of a slit on a distant screen contains maxima and minima, as shown in **Fig. 0.15(a)**. The light is diffracted strongly in the direction perpendicular to the slit edges. A measure of the amount of diffraction is the spacing between the strong central maximum and the first dark fringe in the diffraction pattern. The differences in Fraunhofer and Fresnel diffraction patterns will be explored in **Project #4**.

At distances far from the slit, the Fraunhofer diffraction pattern does not change in shape, but only in size. The fringe separation is expressed in terms of the sine of the angular separation between the central maximum and the center of the first dark fringe,

$$\sin\theta = \frac{\lambda}{w} \qquad (0\text{-}9)$$

where w is the slit width and λ is the wavelength of the light illuminating the slit. Note that as the width of the slit becomes smaller, the diffraction angle becomes larger. If the slit width is not too small, the sine can be replaced by its argument,

$$\theta = \frac{\lambda}{w} \qquad (0\text{-}10)$$

If the wavelength of the light illuminating the slit is known, the diffraction angle can be measured and the width of the diffracting slit determined. In **Project #5** you will be able to do exactly this.

In the case of circular apertures, the diffraction pattern is also circular, as indicated in **Fig. 0.15(b)**, and the angular separation between the central maximum and the first dark ring is given by

$$\sin\theta = 1.22\frac{\lambda}{D}$$

or for large D,

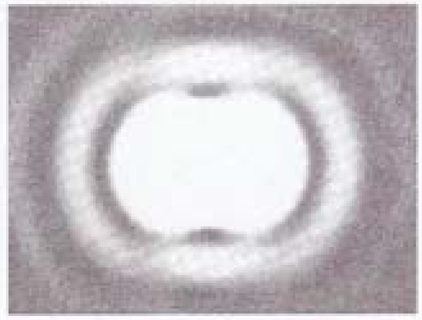
$$\theta = 1.22\frac{\lambda}{D} \qquad (0\text{-}11)$$

where D is the diameter of the aperture. As in the case of the slit, for small values of λ/D, the sine can be replaced by its angle. The measurement of the diameter of different size pinholes is part of **Project #4**.

One good approximation of a point source is a bright star. A pair of stars close to one another can give a measure of the diffraction limits of a system. If the stars have the same brightness, the resolution of the system can be determined by the smallest angular separation between such sources that would still allow them to be resolved. This is provided that the aberrations of the optical system are sufficiently small and diffraction is the only limitation to resolving the images of these two point sources. Although it is somewhat artificial, a limit of resolution that has been used in many instances is that two point sources are just resolvable if the maximum of the diffraction pattern of one point source falls on the first dark ring of the pattern of the second point source, as illustrated in **Fig. 0.16**, then

$$\theta_R = 1.22\frac{\lambda}{D} \qquad (0\text{-}12)$$

This condition for resolution is called the **Rayleigh criterion**. It is used in other fields of optical design, such as specifying the resolution of a optical systems.



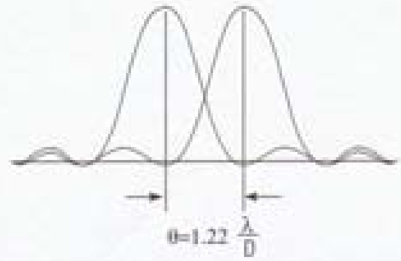


Figure 0.16. Rayleigh criterion. The plot of the intensity along a line between the centers of the two diffraction patterns is shown below a photo of two sources just resolved as specified by the Rayleigh criterion. (Photo by Vincent Mallette)

0.4 Interference

While diffraction provides the limits that tells us how far an optical technique can be extended, interference is responsible for some of the most useful effects in the field of optics — from diffraction gratings to holography. As we shall see, an interference pattern is often connected with some simple geometry. Once the geometry is discovered, the interference is easily understood and analyzed.

0.4.1. Young's Experiment

In **Fig. 0.17** the geometry and wave pattern for one of the simplest interference experiments, Young's experiment, is shown. Two small pinholes, separated by a distance d, are illuminated by a plane wave, producing two point sources that create overlapping spherical waves. The figure shows a cross-sectional view of the wavefronts from both sources in a plane containing the pinholes. Notice that at points along a line equidistant from both pinholes, the waves from the two sources are always in phase. Thus, along the line marked C the electric fields always add in phase to give a field that is twice that of a single field; the irradiance at a point

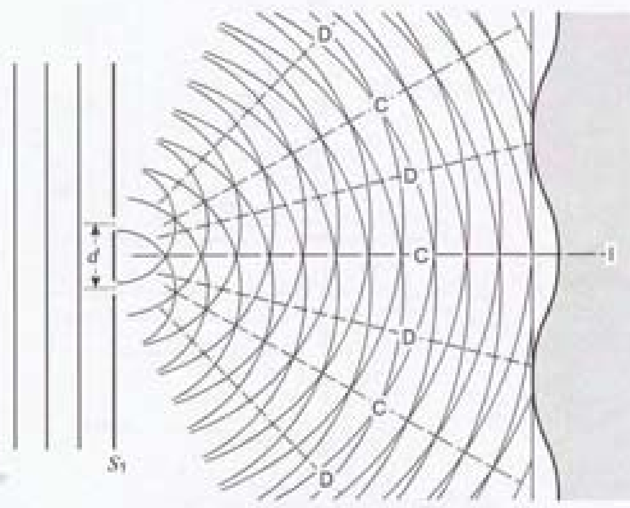


Figure 0.17. Young's Experiment. Light diffracted through two pinholes in screen S_1 spreads out toward screen S_2. Interference of the two spherical waves produces a variation in irradiance (interference fringes) on S_2 that is plotted to the right of the screen.

along the line, which is proportional to the square of the electric field, will be four times that due to a single pinhole. When electric fields add together to give a larger value it is referred to as **constructive interference**. There are other directions, such as those along the dotted lines marked D, in which the waves from the two sources are always 180° out of phase. That is, when one source has a maximum positive electric field, the other has the same negative value so the fields always cancel and no light is detected along these lines marked D, as long as both sources are present. This condition of canceling electric fields is called **destructive interference**. Between the two extremes of maximum constructive and destructive interference, the irradiance varies between four times the single pinhole irradiance and zero. It can be shown that the total energy falling on the surface of a screen placed in the interference pattern is neither more nor less than twice that of a single point source; it is just that interference causes the light distribution to be arranged differently!

Some simple calculations will show that the difference in distances traveled from pinholes to a point on the screen is

$$\Delta r = d \sin\theta. \tag{0-13}$$

In the case of constructive interference, the wavefronts arrive at the screen in phase. This means that there is either one or two or some integral number of wavelength difference between the two paths traveled by the light to the point of a bright fringe. Thus, the angles at which the bright fringes occur are given by

$$\Delta r = d \sin\theta = n\lambda \quad (n = 1, 2, 3, \ldots). \tag{0-14}$$

If the above equation is solved for the angles θ_n at which the bright fringes are found and one applies the approximation that for small angles the sine can be replaced by its angle in radians, one obtains:

$$\theta_n \equiv n\lambda/d \qquad (n = 1, 2, 3, \ldots). \tag{0-15}$$

The angular separation by neighboring fringes is then the difference between θ_{n-1} and θ_n:

$$\Delta\theta = \lambda/d. \tag{0-16}$$

It is this angular separation between fringes that will be measured in **Project #5** to determine the separation between two slits.

0.4.2 The Michelson Interferometer

Another interference geometry that will be investigated in **Project #6** and used to measure an important parameter for a laser in **Project #7** is shown in **Fig. 0.18**. This is a **Michelson interferometer**, which is constructed from a beamsplitter and two mirrors. (This

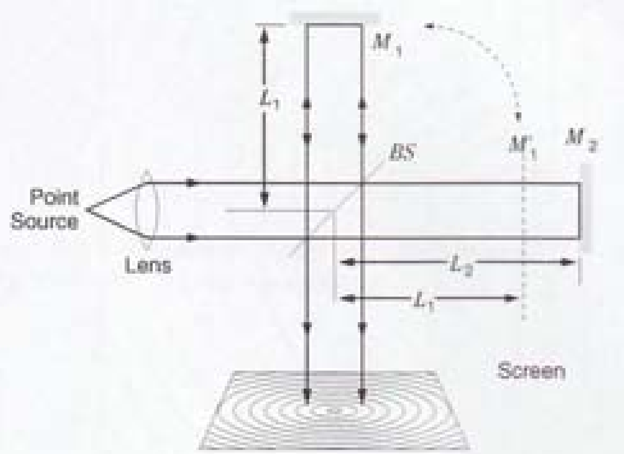


Figure 0.18. Michelson interferometer. By reflecting the mirror M_1 about the plane of the beamsplitter BS to location M'_1, one can see that a ray reflecting off mirror M_2 travels an additional distance $2(L_2 - L_1)$ over a ray reflecting off M_1.

device is sometimes called a **Twyman-Green** interferometer when it is used with a monochromatic source, such as a laser, to test optical components.) The beamsplitter is a partially reflecting mirror that separates the light incident upon it into two beams of equal strength. After reflecting off the mirrors, the two beams are recombined so that they both travel in the same direction when they reach the screen. If the two mirrors are the same distance ($L_1 = L_2$ in **Fig. 0.18**) from the beamsplitter, then the two beams are always in phase once they are recombined, just as is the case along the line of constructive interference in Young's experiment. Now the condition of constructive and destructive interference depends on the difference between the paths traveled by the two beams. Since each beam must travel the distance from the beamsplitter to its respective mirror and back, the distance traveled by the beam is $2L$. If the path-length difference, $2L_1 - 2L_2$, is equal to an integral number of wavelengths, $m\lambda$, where m is an integer, then the two waves are in phase and the interference at the screen will be constructive.

$$L_1 - L_2 = m\lambda/2 \quad (m = \ldots, -1, 0, 1, 2, \ldots). \qquad (0\text{-}17)$$

If the path-length difference is an integral number of wavelengths plus a half wavelength, the interference on the screen will be destructive. This can be expressed as

$$L_1 - L_2 = m\lambda/4 \quad (m = \text{odd integers}). \qquad (0\text{-}18)$$

In most cases the wavefronts of the two beams when they are recombined are not planar, but are spherical wavefronts with long radii of curvature. The interference pattern for two wavefronts of different curvature is a series of bright and dark rings. However, the above discussion still holds for any point on the screen. Usually, however, the center of the pattern is the point used for calculations.

In the above discussion, it was assumed that the medium between the beamsplitter and the mirrors is undisturbed air. If, however, we allow for the possibility that the refractive index in those regions could be different, then the equation for the bright fringes should be written as

$$n_1L_1 - n_2L_2 = m\lambda/2 \quad (m = \ldots -1, 0, 1, 2, \ldots). \qquad (0\text{-}17a)$$

Thus, any change in the refractive index in the regions can also contribute to the interference pattern as you will see in **Project #6**.

In optical system design, interferometers such as the Michelson interferometer can be used to measure very small distances. For example, a movement of one of the mirrors by only one quarter wavelength (corresponding

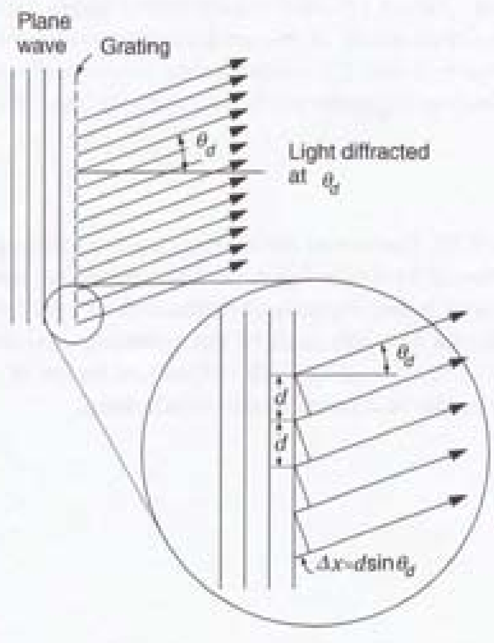


Figure 0.19. Diffraction of light by a diffraction grating.

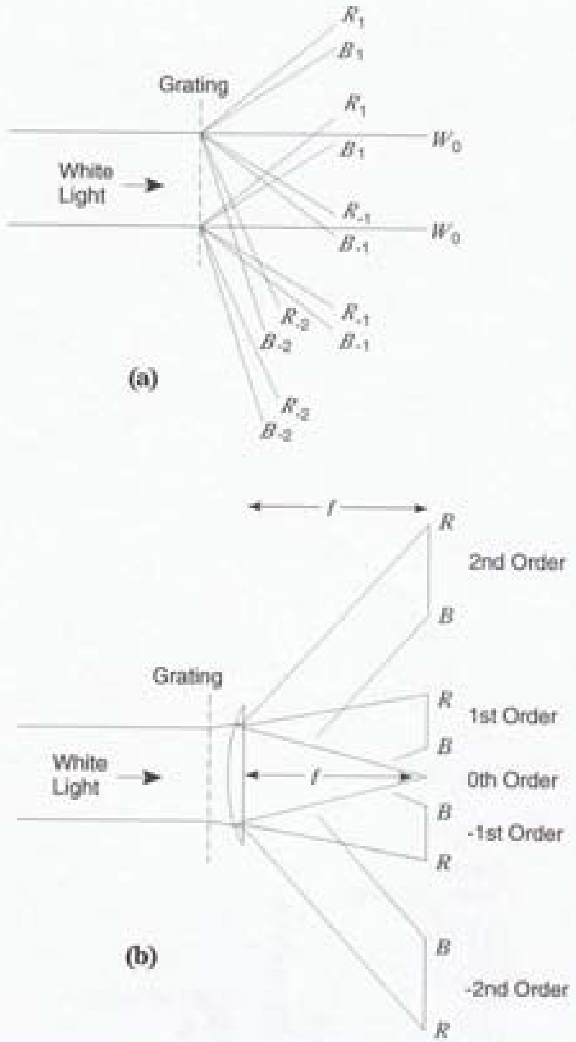


Figure 0.20. Orders of diffraction from a grating illuminated by white light. (a) Rays denoting the upper and lower bounds of diffracted beams for the red (R) and blue (B) ends of the spectrum; (b) spectra produced by focusing each collimated beam of wavelengths to a point in the focal plane.

to a path-length change of one half wavelength) changes the detected irradiance at the screen from a maximum to a minimum. Thus, devices containing interferometers can be used to measure movements of a fraction of a wavelength. One application of interference that has developed since the invention of the laser is holography. This fascinating subject is explored in a separate set of experiments in Newport's **Projects in Holography**.

0.4.3. The Diffraction Grating

It is a somewhat confusing use of the term to call the item under discussion a **diffraction grating**. Although diffraction does indeed create the spreading of light from a regular array of closely spaced narrow slits, it is the combined interference of multiple beams that permits a diffraction grating to deflect and separate the light. In **Fig. 0.19** a series of narrow slits, each separated from its neighboring slits by distance d, are illuminated by a plane wave. Each slit is then a point (actually a line) source in phase with all other slits. At some angle θ_d to the grating normal, the path-length difference between neighboring slits will be (see inset to **Fig. 0.19**)

$$\Delta x = d \sin(\theta_d).$$

Constructive interference will occur at that angle if the path-length difference Δx is equal to an integral number of wavelengths:

$$m\lambda = d \sin(\theta_d) \quad (m = \text{an integer}). \qquad (0\text{-}19)$$

This equation, called the grating equation, holds for any wavelength. Since any grating has a constant slit separation d, light of different wavelengths will be diffracted at different angles. This is why a diffraction grating can be used in place of a prism to separate light into its colors. Because a number of integers can satisfy the grating equation, there are a number of angles into which monochromatic light will be diffracted. This will be examined in **Project #5**. Therefore, when a grating is illuminated with white light, the light will be dispersed into a number of spectra corresponding to the integers $m = \ldots, \pm 1, \pm 2, \ldots$, as illustrated in **Fig. 0.20(a)**. By inserting a lens after the grating, the spectra can be displayed on a screen one focal length from the lens, **Fig. 0.20(b)**. These are called the orders of the grating and are labeled by the value of m.

0.5. Polarization

Since electric and magnetic fields are vector quantities, both their magnitude and direction must be specified. But, because these two field directions are always perpendicular to one another in non-absorbing media, the direction of the electric field of a light wave is used to specify the direction of polarization of the light. The kind and amount of polarization can be determined and modified to other types of polarization. If you understand the polarization properties of light, you can control the amount and direction of light through the use of its polarization properties.

0.5.1. Types of Polarization

The form of polarization of light can be quite complex. However, for most design situations there are a limited number of types that are needed to describe the polarization of light in an optical system. **Fig. 0.21** shows the path traced by the electric field during one full cycle of oscillation of the wave ($T = 1/v$) for a number of different types of polarization, where v is the frequency of the light. **Fig. 0.21(a)** shows **linear polarization**, where orientation of the electric field vector of the wave does not change with time as the field amplitude oscillates from a maximum value in one direction to a maximum value in the opposite direction. The orientation of the electric field is referenced to some axis perpendicular to the direction of propagation. In some cases, it may be a direction in the laboratory or optical system, and it is specified as horizontally or vertically polarized or polarized at some angle to a coordinate axis.

Because the electric field is a vector quantity, electric fields add as vectors. For example, two fields, E_x and E_y, linearly polarized at right angles to each other and oscillating in phase (maxima for both waves occur at the same time), will combine to give another linearly polarized wave, shown in **Fig. 0.21(b)**, whose direction ($\tan\theta = E_y/E_x$) and amplitude ($\sqrt{E_x^2+E_y^2}$) are found by addition of the two components. If these fields are 90° out of phase (the maximum in one field occurs when the other field is zero), the electric field of the combined fields traces out an ellipse during one cycle, as shown in **Fig.0.21(c)**. The result is called **elliptically polarized** light. The eccentricity of the ellipse is the ratio of the amplitudes of the two components. If the two components are equal, the trace is a circle. This polarization is called **circularly polarized**. Since the direction of rotation of the vector depends on the relative phases of the two components, this type of polarization has a handedness to be specified. If the electric field coming from a source toward the observer rotates counterclockwise, the polarization is said to be **left handed. Right-handed polarization** has the opposite sense, clockwise. This nomenclature applies to elliptical as well as circular polarization. Light whose direction of polarization does not follow a simple pattern such as the ones described here is sometimes

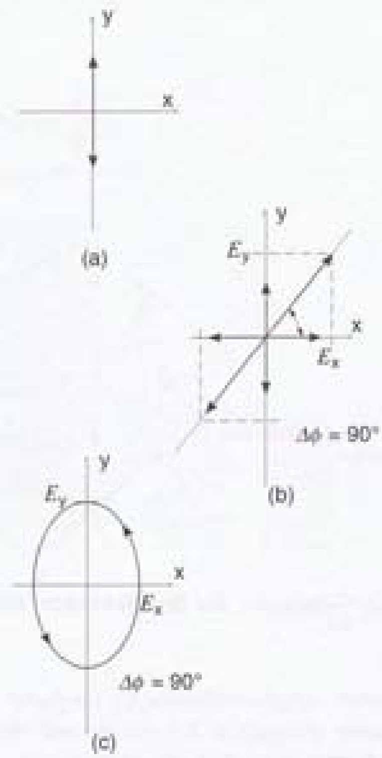


Figure 0.21. Three special polarization orientations: (a) linear, along a coordinate axis; (b) linear, components along coordinate axes are in phase ($\Delta\Phi = 0$) and thus produce linear polarization; (c) same components, 90° out of phase, produce elliptical polarization.

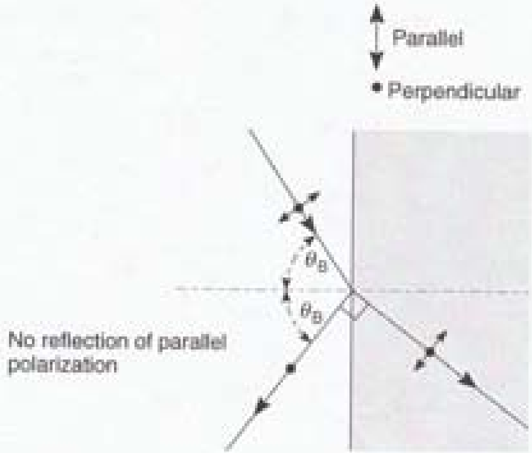


Figure 0.22. Geometry for the Brewster angle.

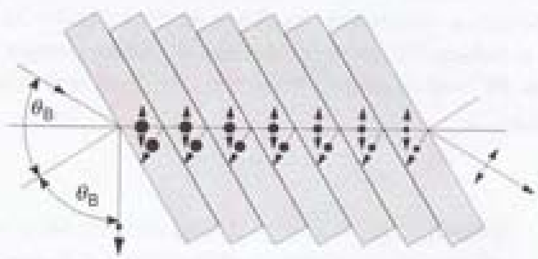


Figure 0.23. A "Pile of Plates" polarizer. This device working at Brewster angle, reflects some portion of the perpendicular polarization (here depicted as a dot, indicating an electric field vector perpendicular to the page) and transmits all parallel polarization. After a number of transmissions most of the perpendicular polarization has been reflected away leaving a highly polarized parallel component.

referred to as unpolarized light. This can be somewhat misleading because the field has an instantaneous direction of polarization at all times, but it may not be easy to discover what the pattern is. A more descriptive term is **randomly polarized light**.

Light from most natural sources tends to be randomly polarized. While there are a number of methods of converting it to linear polarization, only those that are commonly used in optical design will be covered. One method is reflection, since the amount of light reflected off a tilted surface is dependent on the orientation of the incident polarization and the normal to the surface. A geometry of particular interest is one in which the propagation direction of reflected and refracted rays at an interface are perpendicular to each other, as shown in **Fig. 0.22**. In this orientation the component of light polarized parallel to the plane of incidence (the plane containing the incident propagation vector and the surface normal, i.e., the plane of the page for **Fig. 0.22**) is 100% transmitted. There is no reflection for this polarization in this geometry. For the component of light perpendicular to the plane of incidence, there is some light reflected and the rest is transmitted. The angle of incidence at which this occurs is called **Brewster's angle**, θ_B, and is given by:

$$\tan\theta_B = n_{trans}/n_{incident} \qquad (0\text{-}20)$$

As an example, for a crown glass, $n = 1.523$, and the Brewster angle is 56.7°. Measurement of Brewster's angle is part of **Project #8**.

Sometimes only a small amount of polarized light is needed, and the light reflected off of a single surface tilted at Brewster's angle may be enough to do the job. If nearly complete polarization of a beam is needed, one can construct a linear polarizer by stacking a number of glass slides (e.g., clean microscope slides) at Brewster's angle to the beam direction. As indicated in **Fig. 0.23**, each interface rejects a small amount of light polarized perpendicular to the plane of incidence.

The "pile of plates" polarizer just described is somewhat bulky and tends to get dirty, reducing its efficiency. Plastic polarizing films are easier to use and mount. These films selectively absorb more of one polarization component and transmit more of the other. The source of this polarization selection is the aligned linear chains of a polymer to which light-absorbing iodine molecules are attached. Light that is polarized parallel to the chains is easily absorbed, whereas light polarized perpendicular to the chains is mostly transmitted. The sheet polarizers made by Polaroid Corporation are labeled by their type and transmission. Three common linear polarizers are **HN-22**, **HN-32**, and **HN-38**, where the number following the HN indicates the percentage of incident unpolarized light that is transmitted through the polarizer as polarized light.

When you look through a crystal of calcite (calcium carbonate) at some writing on a page, you see a double image. If you rotate the calcite, keeping its surface on the page, one of the images rotates with the crystal while the other remains fixed. This phenomenon is known as double refraction. (Doubly refracting is the English equivalent for the Latin **birefringent.**) If we examine these images through a sheet polarizer, we find that each image has a definite polarization, and these polarizations are perpendicular to each other.

Calcite crystal is one of a whole class of birefringent crystals that exhibit double refraction. The physical basis for this phenomenon is described in detail in most optics texts. For our purposes it is sufficient to know that the crystal has a refractive index that varies with the direction of propagation in the crystal and the direction of polarization. The **optic axis** of the crystal (no connection to the optical axis of a lens or a system) is a direction in the crystal to which all other directions are referenced. Light whose component of the polarization is perpendicular to the optic axis travels through the crystal as if it were an ordinary piece of glass with a single refraction index, n_0. Light of this polarization is called an **ordinary ray**. Light polarized parallel to a plane containing the optic axis has a refractive index that varies between n_0 and a different value, n_e. The material exhibits a refractive index n_e where the field component is parallel to the optic axis and the direction of light propagation is perpendicular to the optic axis. Light of this polarization is called an **extraordinary ray**. The action of the crystal upon light of these two orthogonal polarization components provides the double images and the polarization of light by transmission through the crystals. If one of these components could be blocked or diverted while the other component is transmitted by the crystal, a high degree of polarization can be achieved.

In many cases polarizers are used to provide information about a material that produces, in some manner, a change in the form of polarized light passing through it. The standard configuration, shown in **Fig. 0.24**, consists of a light source *S*, a polarizer *P*, the material M, another polarizer, called an analyzer *A*, and a detector *D*. Usually the polarizer is a linear polarizer, as is the analyzer. Sometimes, however, polarizers that produce other types of polarization are used.

The amount of light transmitted by a polarizer depends on the polarization of the incident beam and the quality

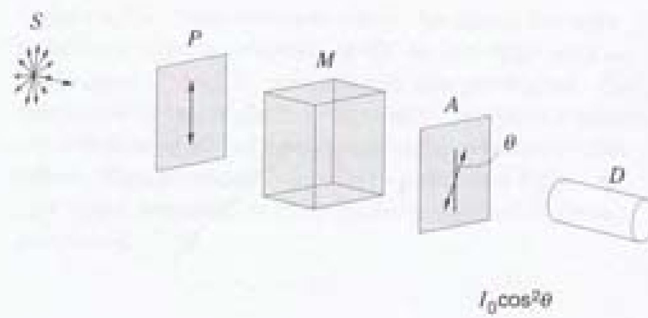


Figure 0.24. Analysis of polarized light. Randomly polarized light from source S is linearly polarized after passage through the polarizer P with irradiance I_0. After passage through optically active material M, the polarization vector has been rotated through an angle θ. (The dashed line of both polarizers A and P denote the transmission axes; the arrow indicates the polarization of the light.) The light is analyzed by polarizer A, transmitting an amount $I_0\cos^2\theta$ that is detected by detector D.

of the polarizer. Let us take, for example, a perfect polarizer — one that transmits all of the light for one polarization and rejects (by absorption or reflection) all of the light of the other polarization. The direction of polarization of the transmitted light is the polarization axis, or simply the axis of the polarizer. Since randomly polarized light has no preferred polarization, there would be equal amounts of incident light for two orthogonal polarization directions. Thus, a perfect linear polarizer would have a Polaroid designation of HN-50, since it would pass half of the incident radiation and absorb the other half. The source in **Fig. 0.24** is randomly polarized, and the polarizer passes linearly polarized light of irradiance I_0. If the material M changes the incident polarization by rotating it through an angle θ, what is the amount of light transmitted through an analyzer whose transmission axis is oriented parallel to the axis of the first polarizer? Since the electric field is a vector, we can decompose it into two components, one parallel to the axis of the analyzer, the other perpendicular to this axis. That is

$$\vec{E} = E_0 \cos\theta\, \hat{e}_{\parallel} + E_0 \sin\theta\, \hat{e}_{\perp} \qquad (0\text{-}21)$$

(Note that the parallel and perpendicular components here refer to their orientation with respect to the axis of the analyzer and not to the plane of incidence as in the case of the Brewster angle.) The transmitted field is the parallel component, and the transmitted irradiance I_{trans} is the time average square of the electric field

$$I_{trans} = \langle E_0^2 \cos^2\theta \rangle = \langle E_0^2 \rangle \cos^2\theta$$

or

$$I_{trans} = I_0 \cos^2\theta \qquad (0\text{-}22)$$

This equation, which relates the irradiance of polarized light transmitted through a perfect polarizer to the irradiance of incident polarized light, is called the **Law of Malus**, after its discoverer, Etienne Malus, an engineer in the French army. For a nonperfect polarizer, I_0 must be replaced by αI_0, where α is the fraction of the preferred polarization transmitted by the polarizer.

0.5.2. Polarization Modifiers

Besides serving as linear polarizers, birefringent crystals can be used to change the type of polarization of a light beam. We shall describe the effect that these polarization modifiers have on the beam and leave the explanation of their operation to a physical optics text.

In a birefringent crystal, light whose polarization is parallel to the optic axis travels at a speed of $c/n_{\parallel}$; for a polarization perpendicular to that, the speed is $c/n_{\perp}$. In calcite $n_{\perp} > n_{\parallel}$, and therefore the speed of light polarized parallel to the optic axis, $v_{\parallel}$, is greater than $v_{\perp}$.

Thus, for calcite, the optic axis is called the fast axis and a perpendicular axis is the slow axis. (In other crystals $n_{\parallel}$ may be greater than $n_{\perp}$ and the fast-slow designation would have to be reversed.)

The first device to be described is a **quarter-wave plate.** The plate consists of a birefringent crystal of a specific thickness *d*, cut so that the optic axis is parallel to the plane of the plate and perpendicular to the edge, as shown in **Fig.0.25**. The plate is oriented so that its plane is perpendicular to the beam direction and its fast and slow axes are at 45° to the polarized direction of the incident linearly polarized light. Because of this 45° geometry, the incident light is split into slow and fast components of equal amplitude traveling through the crystal. The plate is cut so that the components, which were in phase at the entrance to the crystal, travel at different speeds through it and exit at the point when they are 90°, or a quarter wave, out of phase. This output of equal amplitude components, 90° out of phase, is then circularly polarized. It can be shown that when circularly polarized light is passed through the same plate, linearly polarized light results. Also, it should be noted that if the 45° input geometry is not maintained, the output is elliptically polarized. The angle between the input polarization direction and the optic axis determines the eccentricity of the ellipse.

If a crystal is cut that has twice the thickness of the quarter-wave plate, one has a **half-wave plate**. In this case, linearly polarized light at any angle θ with respect to the optic axis provides two perpendicular components which end up 180° out of phase upon passage through the crystal. This means that relative to one of the polarizations, the other polarization is 180° from its original direction. These components can be combined, as shown in **Fig. 0.26**, to give a resultant whose direction has been rotated 2θ from the original polarization. Sometimes a half-wave plate is called a **polarization rotator.** It also changes the "handedness" of circular polarization from left to right or the reverse. This discussion of wave plates assumes that the crystal thickness *d* is correct only for the wavelength of the incident radiation. In practice, there is a range of wavelengths about the correct value for which these polarization modifiers work fairly well.

Waveplates provide good examples of the use of polarization to control light. One specific demonstration that you will perform as part of **Project #9** concerns reflection reduction. Randomly polarized light is sent through a polarizer and then through a quarter wave plate to create circularly polarized light, as noted above. When circularly polarized light is reflected off a

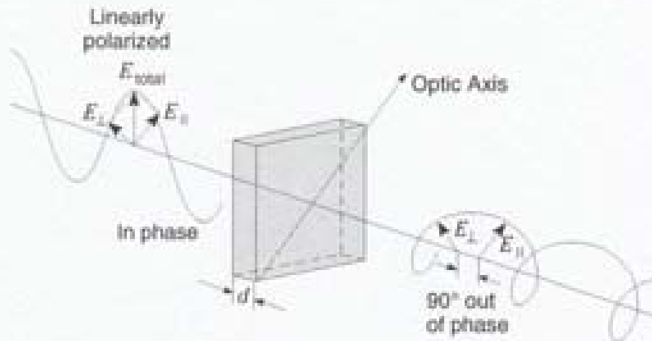


Figure 0.25. Quarter-wave plate. Incident linearly polarized light is oriented at 45° to the optic axis so that equal $E_{\parallel}$ and $E_{\perp}$ components are produced. The thickness of the plate is designed to produce a phase retardation of 90° of one component relative to the other. This produces circularly polarized light. At any other orientation elliptically polarized light is produced.

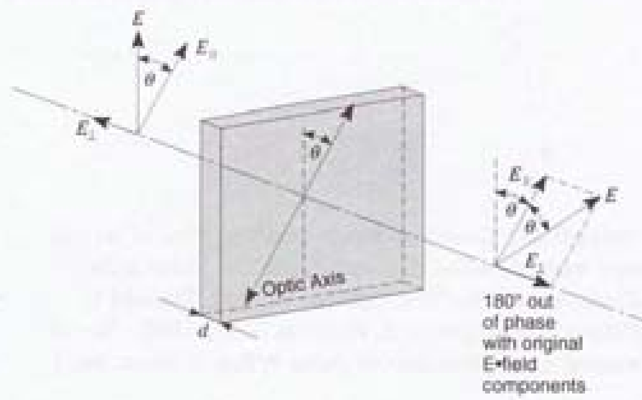


Figure 0.26. Half-wave plate. The plate produces a 180° phase lag between the $E_{\parallel}$ and $E_{\perp}$ components of the incident linearly polarized light. If the original polarization direction is at an angle θ to the optic axis, the transmitted polarization is rotated through 2θ from the original.

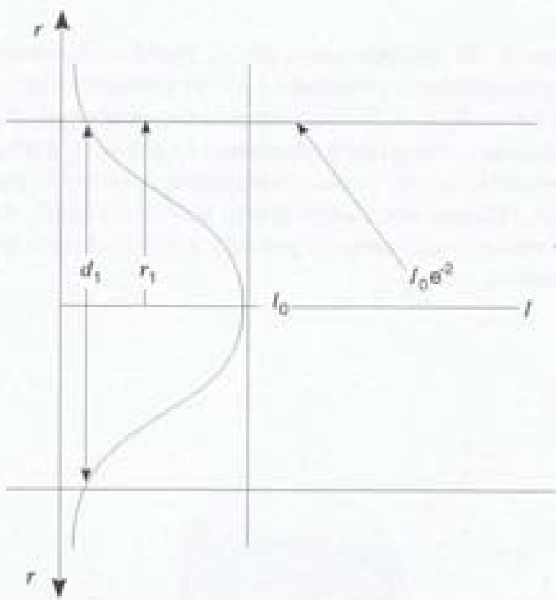


Figure 0.27. Gaussian beam profile. Plot of irradiance versus radial distance from the beam axis. [*Elements of Modern Optical Design*, Donald C. O'Shea, copyright ©, J. Wiley & Sons, 1985. Reprinted by permission of John Wiley & Sons, Inc.]

surface, its handedness is reversed (right to left or left to right). When the light passes through the quarter wave plate a second time, the circularly polarized light of the opposite handedness is turned into linearly polarized light, but rotated 90° with respect to the incident polarization. Upon passage through the linear polarizer a second time, the light is absorbed. However, light emanating from behind a reflective surface (computer monitor, for example) will not be subject to this absorption and a large portion will be transmitted by the polarizer. A computer anti-reflection screen is an application of these devices. Light from the room must undergo passage through the polarizer-waveplate combination twice and is, therefore suppressed, whereas light from the computer screen is transmitted through the combination but once and is only reduced in brightness. Thus, the contrast of the image on the computer screen is enhanced significantly using this polarization technique.

0.6 Lasers

The output of a laser is very different than most other light sources. After a description of the simplest type of beam, the TEM_{00} mode Gaussian beam and its parameters, we look at means of collimating the beam. The effect of a laser's construction on its output and a method by which this output can be measured will be discussed.

0.6.1. Characteristics of a Gaussian Beam

The term **Gaussian** describes the variation in the irradiance along a line perpendicular to the direction of propagation and through the center of the beam, as shown in **Fig. 0.27**. The irradiance is symmetric about the beam axis and varies radially outward from this axis with the form

$$I(r) = I_0 e^{-2r^2/r_1^2} \qquad (0\text{-}23)$$

or in terms of a beam diameter

$$I(d) = I_0 e^{-2d^2/d_1^2}$$

where r_1 and d_1 are the quantities that define the radial extent of the beam. These values are, by definition, the radius and diameter of the beam where the irradiance is $1/e^2$ of the value on the beam axis, I_0.

0.6.1.1. Beam Waist and Beam Divergence

Figure 0.27 shows a beam of parallel rays. In reality, a Gaussian beam either diverges from a region where the beam is smallest, called the **beam waist**, or converges to one, as shown in **Fig. 0.28**. The amount of divergence or convergence is measured by the **full angle beam divergence** θ, which is the angle subtended by the $1/e^2$ diameter points for distances far from the beam waist as shown in **Fig. 0.28**. In some laser texts and articles, the angle is measured from the beam axis to the $1/e^2$ asymptote, a *half* angle. However, it is the full angle divergence, as defined here, that is usually given in the specification sheets for most lasers. Because of symmetry on either side of the beam waist, the convergence angle is equal to the divergence angle. We will refer to the latter in both cases.

Under the laws of geometrical optics a Gaussian beam converging at an angle of θ should collapse to a point. Because of diffraction, this, does not occur. However, at the intersection of the asymptotes that define θ, the beam does reach a minimum value d_0 the **beam waist diameter**. It can be shown that for a TEM_{00} mode d_0 depends on the beam divergence angle as:

$$d_0 = \frac{4\lambda}{\pi\theta} \qquad (0\text{-}24)$$

where λ is the wavelength of the radiation. Note that for a Gaussian beam of a particular wavelength, the product $d_0\theta$ is constant. Therefore for a very small beam waist the divergence must be large, for a highly collimated beam (small θ), the beam waist must be large.

The variation of the beam diameter in the vicinity of the beam waist is shown in **Fig. 0.28** and given as

$$d^2 = d_0^2 + \theta^2 z^2 \qquad (0\text{-}25)$$

where d is the diameter at a distance $\pm z$ from the waist along the beam axis.

0.6.1.2. The Rayleigh Range

It is useful to characterize the extent of the beam waist region with a parameter called the **Rayleigh range**. (In other descriptions of Gaussian beams this extent is sometimes characterized by the confocal beam parameter and is equal to twice the Rayleigh range.) Rewriting **Eq. 0.25** as

$$d = d_0\sqrt{1 + (\theta z / d_0)^2} \qquad (0\text{-}26)$$

we define the Rayleigh range as the distance from the beam waist where the diameter has increased to $d_0\sqrt{2}$. Obviously this occurs when the second term under the radical is unity, that is, when

$$z = z_R = d_0/\theta \qquad (0\text{-}27)$$

Although the definition of z_R might seem rather arbitrary, this particular choice offers more than just convenience. **Figure 0.29** shows a plot of the radius of curvature of the wavefronts in a Gaussian beam as a function of z. For large distances from the beam waist the wavefronts are

Figure 0.28. Variation of Gaussian beam diameter in the vicinity of the beam waist. The size of the beam at its smallest point is d_0; the full angle beam divergence, defined by the smallest asymptotes for the $1/e^2$ points at a large distance from the waist is θ.

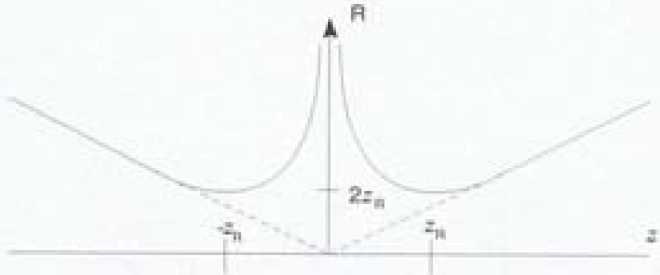


Figure 0.29. Plot of radius of curvature (R) versus distance (z) from the beam waist. The absolute value of the radius is a minimum at the Rayleigh range point, z_R. In the limit of geometrical optics, the radius of curvature of the wavefronts follows the dashed line.

nearly planar, giving values tending toward infinity. At the beam waist the wavefronts are also planar, and, therefore, the absolute value of the radius of curvature of the wavefronts must go from infinity at large distances through a minimum and return to infinity at the beam waist. This is also true on the other side of the beam waist but with the opposite sign. It can be shown that the minimum in the absolute value of the radius of curvature occurs at $z = \pm z_R$, that is, at a distance one Rayleigh range either side of the beam waist. From **Fig. 0.29**, the "collimated" region of Gaussian beam waist can be taken as $2z_R$.

The Rayleigh range can be expressed in a number of ways:

$$z_R = \frac{d_0}{\theta} = \frac{4\lambda}{\pi\theta^2} = \frac{\pi d_0^2}{4\lambda} \qquad \text{(0-28)}$$

From this we see that all three characteristics of a Gaussian beam are dependent on each other. Given any of the three quantities, d_0, θ, z_R, and the wavelength of the radiation, the behavior of the beam is completely described. Here, for example, if a helium-neon laser ($\lambda = 633$ nm) has a specified TEM_{00} beam diameter of 1 mm, then

$\theta = 4\lambda/\pi d_0 = (1.27 \times 6.33 \times 10^{-7}\text{m})/(1 \times 10^{-3}\text{m}) = 0.8$ mrad

and

$z_R = d_0/\theta = (1 \times 10^{-3}\text{m})/(0.8 \times 10^{-3}\text{rad}) = 1.25$ m.

The Rayleigh range of a typical helium-neon laser is considerable.

0.6.2 Collimation of a Laser Beam

Through the use of lenses the divergence, beam waist, and Rayleigh range of the Gaussian beam can be changed. However, from the above discussion it is clear that the relations between the various beam parameters cannot be changed. Thus, to increase the collimation of a beam by reducing the divergence requires that the beam waist diameter be increased, since the beam waist diameter-divergence product is constant. This is done by first creating a beam with a strong divergence and small beam waist and then putting the beam waist at the focal point of a long focal length lens. What this amounts to is putting the beam through a telescope — backward. The laser beam goes in the eyepiece lens and comes out the objective lens.

There are two ways of accomplishing this. One uses a Galilean telescope, which consists of a negative eyepiece lens and a positive objective lens, as shown in **Fig. 0.30(a)**. The light is diverged by the negative lens producing a virtual beam waist and the objective lens is positioned at a separation equal to the algebraic sum of the focal lengths of the lenses to produce a more collimated beam. It can be shown that the decrease in the divergence is equal to the original divergence divided by the magnification of the telescope. The magnification of the telescope is equal to the ratio of the focal lengths of the objective divided by the eyepiece The second method uses a Keplerian telescope (**Fig. 0.30(b)**). The eyepiece lens is a positive lens so the beam comes to a focus and then diverges to be collimated by the objective lens.

Project #3 will demonstrate the design of these two types of laser beam expanders. Each has distinct advantages. The advantage of the Galilean type of beam expander occurs for high power or pulsed laser systems. Since the beam does not come to a focus anywhere inside of the beam expander's optical path, the power density of the beam decreases. Thus, if the lenses and environment can survive the initial beam, they can survive the beam anywhere in the optical path. Although the Keplerian beam expander can give similar ratios of beam expansion, the power density at the focus of the first lens is very large. In fact, with a high power, pulsed laser it is possible to cause a breakdown of the air in the space between the lenses. This breakdown is caused by the very strong electrical field that results from focusing the beam to a small diameter creating miniature lightning bolts. (Many researchers have been unpleasantly surprised when these "miniature" lightning bolts destroyed some very expensive optics!)

The primary advantage for the Keplerian beam expander is that a pinhole of an optimum diameter can be placed at the focus of the first lens to "clean" up the laser beam by rejecting the part of the laser energy that is outside of the pinhole diameter. This concept of **"spatial filtering"** will be explored in **Project #10**.

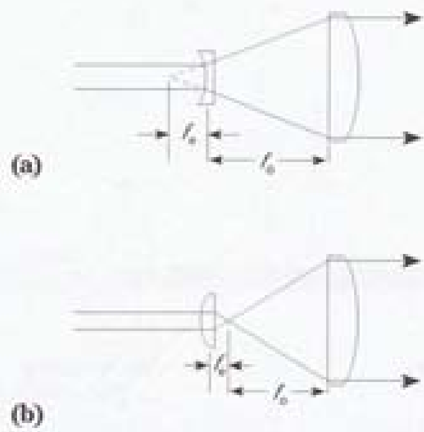


Figure 0.30. Gaussian beam collimation. (a) Galilean telescope. (b) Keplerian telescope. Eyepiece focal length, f_e; objective focal length, f_o.

0.6.3 Axial Modes of a Laser

The properties of laser light include monochromaticity, low divergence (already explored in the previous sections), and a high degree of coherence, which encompasses both of these properties. This section is a discussion of the coherence of the laser and a historical experiment that illustrates one of the concepts using a modern device.

A complete discussion of the principle of laser action would take a substantial amount of space and reading time. For an explanation of the concept we refer you to the references. The basis of lasers is a physical process called stimulated emission. It appears as the third and fourth letters of the acronym, **LASER** (**L**ight **A**mplification by **S**timulated **E**mission of **R**adiation). Amplification is only the beginning of the process in most lasers, since the increase in light as it passes through an amplifying volume is usually quite modest. If the radiation was only amplified during a single pass through the volume, it would be only marginally useful. However, when mirrors are placed at both ends of the amplifying medium, the light is returned to the medium for additional amplification **(Fig. 0.31)**. The useful output from the laser comes through one of the mirrors, which reflects most of the light, but transmits a small fraction of the light, usually on the order of 5% (up to 40% for high power lasers). The other mirror is totally reflecting. But the laser mirrors do more than confine most of the light. They also determine the distribution of wavelengths that can support amplification in the laser.

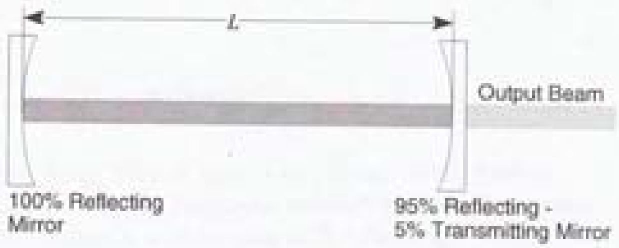


Figure 0.31. The laser cavity. The distance between mirrors is an important parameter in the output of a laser.

The mirrors serve as a simple, but effective, interferometer and for only certain wavelengths, just as in the case of the Michelson interferometer, will there be constructive interference. The mirrors form a resonant structure that stores or supports only certain frequencies. It is best compared to the resonances of a guitar string in which the note that the string produces when plucked is determined by the length of the string. By changing the location of the finger on a guitar string a different note is played. The note (really, notes) is determined by the amount of tension the guitarist has put on the string and the length of the string. Any fundamental physics book will show that the conditions imposed upon the string of length L will produce a note whose wavelength is such that an integral number of half wavelengths is equal L,

$$q\lambda/2 = L. \qquad \text{(0-29)}$$

In **Fig. 0.32** a **standing wave** with three half wavelengths is shown. In most lasers, unless special precautions are taken, a number of wavelengths will satisfy this resonance condition. These wavelengths are referred to as the **axial modes** of the laser. Since $L = q\lambda/2$, where q is an integer, the wavelengths supported by the laser are

$$\lambda_q = 2L/q \qquad \text{(0-29a)}$$

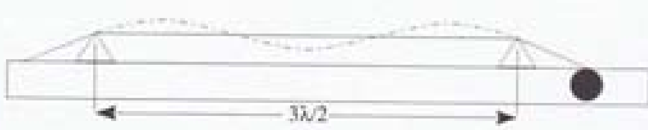


Figure 0.32. Standing wave picture.

The frequencies of these modes are given by $\nu = c/\lambda$, where c is the speed of light.

Inserting the expression for the wavelengths, the frequencies of the resonant modes are given by

$$\nu_q = q\,(c/2L),$$

where q is an integer. The frequency separation between these axial modes equals the difference between modes whose integers differ by one:

$$\Delta n = \nu_{q+1} - \nu_q = (q+1)c/2L - qc/2L = c/2L, \qquad (0\text{-}30)$$

so the separation between neighboring modes of a laser is constant and dependent only on the distance between the mirrors in the laser, as shown in **Fig. 0.33**. Since the amount of power obtained from small helium-neon lasers, such as those used for the projects described in this manual, is related to the **length** of the laser, the separation between mirrors is set by the laser manufacturers to produce the required power for the laser. But the band of wavelengths that can maintain stimulated emission is determined by the atomic physics of the lasing medium, in this case, neon. That band does not change radically for most helium-neon laser tubes. Therefore, the **number** of axial modes is mainly dependent on the distance between the mirrors, L. The farther apart the mirrors are, the closer are the axial mode frequencies. Thus, long high power helium-neon lasers have a large number of axial modes, whereas, the modest power lasers used in this **Projects in Optics** kit produce only a small number (usually three) of axial modes.

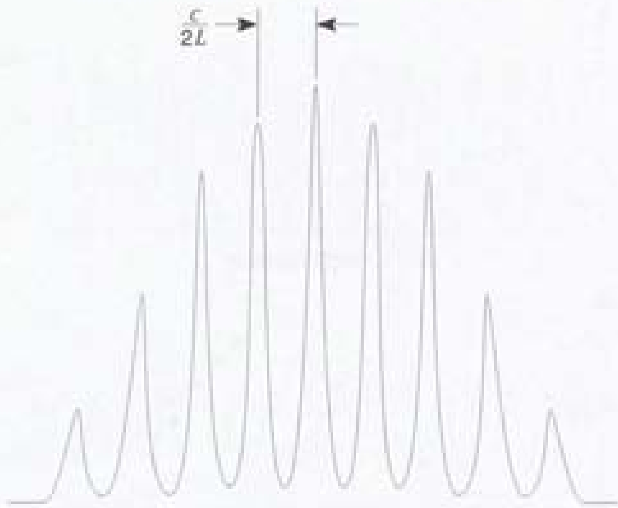


Figure 0.33. Laser mode distribution. Plot of power in laser output as a function of frequency.

One of the other relations between neighboring laser modes, beside their separation, is that their polarization is orthogonal (crossed) to that of their neighbors (**Fig. 0.34**). Thus, if we examined a three-mode laser with the appropriate tools, we would expect to find that two of the modes would have one polarization and the other would have a perpendicular polarization. This means that, while axial modes are separated in frequency by $c/2L$, modes of the **same polarization** are separated by c/L.

Looking through a diffraction grating at the output of a three-mode laser, we see a single color. High resolution interferometers must be employed to display the axial modes of a laser. However, it is also possible to use a Michelson interferometer to investigate the modes without resorting to high resolution devices. This technique has special applications in the infrared region of the spectrum.

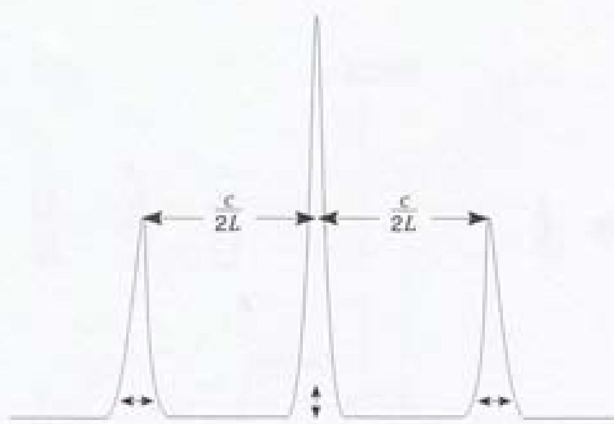


Figure 0.34. Output from a three mode laser. The relative polarization of each mode is indicated at its base.

0.6.4 Coherence of a Laser

If we speak of something as being "coherent" in everyday life, we usually mean that it, a painting, a work of music, a plan of action, "makes sense." It "hangs together." There is in this concept the idea of consistency and predictability. The judgement of what is coherent, however, is one of individual taste. What one person may find coherent in heavy metal rock music, another person would hear in rhythm and blues ... or elevator music, perhaps. This concept of coherence as a predictable, consistent form of some idea or work of art has much the same meaning when applied to light

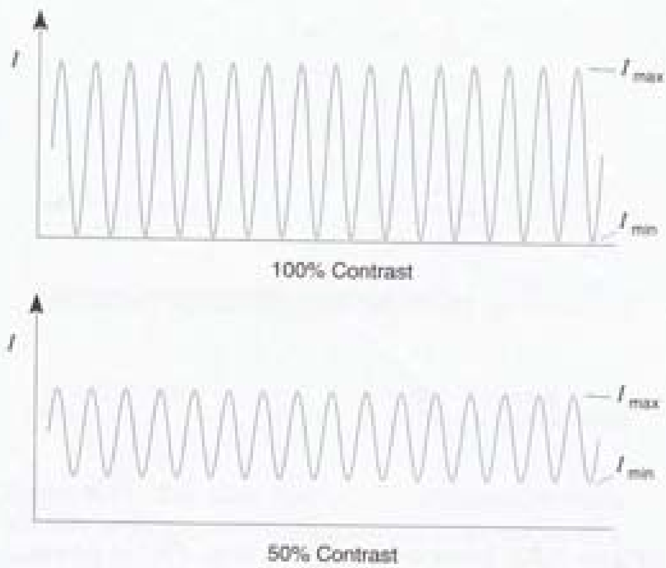


Figure 0.35. Contrast.

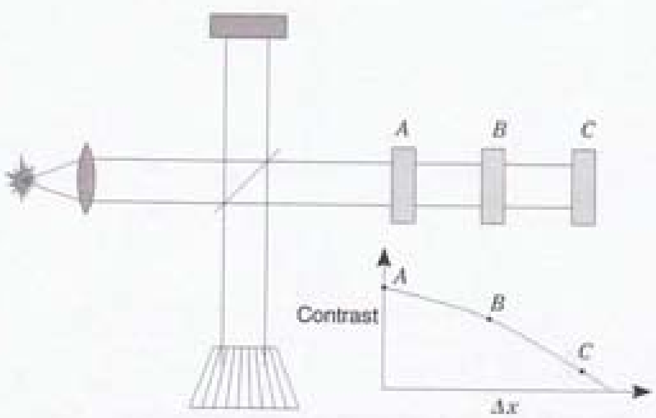


Figure 0.36. Visibility function.

sources. How consistent is a light field from one point to another? How do you make the comparison? The interference of the light beam with itself does the comparing. If there is a constant relation between one point on a laser beam and another point, then the interference of waves separated by that distance should produce a stable interference pattern. If, however, the amplitude or phase or wavelength changes between these two points, the interference, while it is still there at all times, will constantly vary with time. This unstable interference pattern may still exhibit fringes, but the fringes will be washed out. This loss of visibility of fringes as a function of the distance between the points of comparison is measure of the coherence of the light. This visibility can be measured by the **contrast** of the interference fringes. The contrast is defined by

$$C = \frac{I_{max} - I_{min}}{I_{max} + I_{min}} \qquad (0\text{-}31)$$

where I_{max} is the irradiance of the bright interference fringes and I_{min} is the irradiance of the dark interference fringes (**Fig. 0.35**). This contrast is determined by passing the light from the source through a Michelson interferometer with unequal arms. By changing the path length difference between the arm in the interferometer, the visibility of the fringes as a function of this difference can be recorded. From these observations, the measurement of the coherence of a source can be done using a Michelson interferometer.

If a source were absolutely monochromatic, there would be no frequency spread in its spectrum. That is, its frequency bandwidth would be zero. For this to be true, all parts of the wave exhibit the same sinusoidal dependence from one end of the wave to the other. Thus, a truly monochromatic wave would never show any lack of contrast in the fringes, no matter how large of a path length difference was made. But all sources, even laser sources contain a distribution of wavelengths. Therefore, as the path length difference is increased, the wavefront at one point on the beam gets out of phase with another point on the beam. A measure of the distance at which this occurs is the coherence length l_c of a laser. It is related to the frequency bandwidth of a laser by

$$\Delta v = c / l_c \qquad (0\text{-}32)$$

Any measurement of the coherence length of a light source by observation of the visibility of fringes from a Michelson interferometer will yield information on the bandwidth of that source and, therefore, its coherence. For example, suppose the source is a laser with some broadening. As the length of the one of the arms in a

Michelson interferometer, as shown in **Fig. 0.36**, becomes unequal (mirror moved from A to B), the one part of a wave will interfere with another part that is delayed by a time equal to the difference in path length divided by the speed of light. Eventually the waves begin to get out of step and the fringe contrast begins to fall because the phase relations between the two waves is varying slightly due to the spread in frequencies in the light. The greater the broadening, the more rapidly the visibility of the fringes will go to zero.

One particularly interesting case consists of a source with only a few modes present as is the case for the three-mode helium-neon laser discussed above. Because only light of the same polarization can interfere, there will be two modes (λ_1, λ_3) in the laser that can interfere with each other. The third mode (λ_2) with orthogonal polarization is usually eliminated by passing the output of the laser through a polarizer. With the interferometer mirrors set at equal path length there are two sets of fringes, one from each mode. Since the path length difference is zero, these two sets of high contrast fringes overlap each other. But as the path length increases, the fringes begin to get out of step. Until, finally, the interference maximum of one set of fringes overlaps the interference minimum of the other set of fringes and the fringe contrast goes to zero. The calculation of this condition is fairly simple. The condition for an interference maximum is given by

$$L_1 - L_2 = m\lambda/2 \quad m = \text{an integer} \tag{0-33}$$

and for an interference minimum by

$$L_1 - L_2 = m\lambda/4 \quad m = \text{odd integers} \tag{0-34}$$

If we assume that the change in path length is from zero path length to the point where the visibility first goes to zero, then for one wavelength, λ_1,

$$L_1 - L_2 = m\lambda_1/2 \quad m = \text{an integer} \qquad (0\text{-}35)$$

and for the other mode with the same polarization, there is a minimum.

$$L_1 - L_2 = m\lambda_3/2 + \lambda_3/4 \qquad (0\text{-}35)$$

Equating these two expressions and rearranging terms, gives

$$m\lambda_1/2 - m\lambda_3/2 = m(\lambda_1 - \lambda_3)/2 = \lambda_3/4. \qquad (0\text{-}35)$$

or

$$m\Delta\lambda = \lambda_3/2$$

Wavelength separation can be expressed as a frequency separation by $\Delta\nu$

$$\Delta\lambda = \lambda\Delta\nu/\nu \tag{0-36}$$

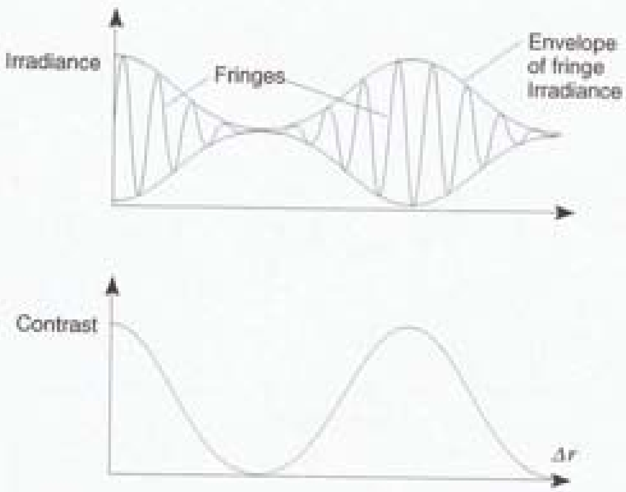


Figure 0.37. Visibility function for two mode system.

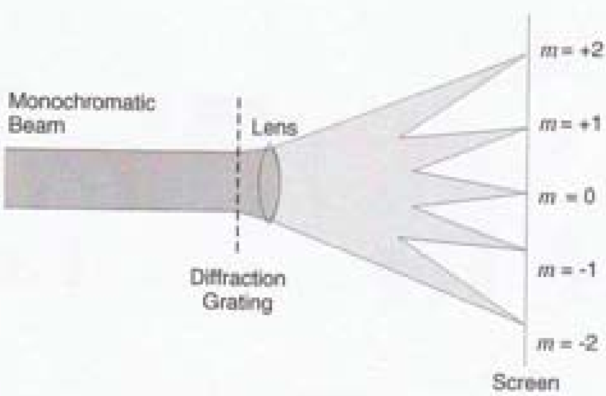


Figure 0.38. Diffraction orders.

where λ and v are the average values in the intervals $\Delta\lambda$ and Δv. Inserting this expression for $\Delta\lambda$, we obtain

$$\Delta v = v/2m \,. \tag{0-37}$$

The integer m is an extremely large number in most cases and is not easily determined, but it is related to the average wavelength of the source by $L_1 - L_2 = m\lambda/2$. If we set $\Delta L = L_1 - L_2$, solve for m and insert in the expression for Δv,

$$\Delta v = v/2m = \lambda v/4\Delta L = c/4\Delta L, \tag{0-38}$$

since $\lambda v = c$.

Thus the frequency separation between modes can be measured by determining the path length difference when the two interference fringe patterns are out of step with one another, causing the visibility to go to zero, as depicted in **Fig. 0.37**. It can also be demonstrated that there are additional minima in the visibility at $\Delta v = 3c/4\Delta L$, $5c/4\Delta L$, etc. Visibility maxima occur halfway between these minima as the two fringes patterns get back into step. In **Project#7**, this effect will enable you to determine the mode separations for the laser used in these projects. What has been derived here is a simple case of a much more involved application of this technique. It is possible to measure the fringe contrast as a function of mirror position (called an interferogram) and store it in the memory of a computer. It has been shown that a mathematical transformation (the same Fourier Transform that will be discussed in the next section) of the visibility function yields the frequency spectrum of the source.

While it might be considered difficult, the advent of powerful computers has reduced the cost and enhanced the utility of this technique, particularly in the far infrared part of the spectrum. These devices are known as Fourier transform spectrometers.

0.7 Abbe Theory of Imaging

The earlier discussion of imaging depended upon tracing a series of rays to determine the location and size of the image. It was shown that only a few rays were needed. This approach ignores the possibilities that the source could be monochromatic and sufficiently coherent that diffraction and interference effects could play a part in the formation of an image. What we will describe and then demonstrate in **Project #10**, is that after the light that will form an image has traversed the lens, we can intervene and change the image in very special ways. This approach to imaging has found use in a number of applications in modern optics. To begin to understand this concept, we need to review briefly the diffraction grating discussed in **Section 0.4.3**, since the grating is one of the simplest illustrations of this new way of thinking about imaging. Consider a diffraction grating consisting of a series of equally spaced, narrow absorbing and transmitting (black and white) bands. It is possible to determine mathematically not only the directions of the diffracted orders

$$\sin\theta_m = m\,\lambda/d \qquad m = \text{an integer,} \qquad (0\text{-}39)$$

but also the relative irradiances of the diffracted spots to one another. If we insert a lens after the diffraction grating, we can relocate the orders of the diffraction grating from infinity to the back focal plane of the lens **(Fig. 0.38)**. We will see how this can be used to understand imaging.

0.7.1 Spatial Frequencies

We are used to the idea of repetitions in time. Electrical and audio sources of signals with single frequencies, particularly as they relate to sound are used to test equipment for their response. A good high fidelity system will reproduce a wide range of frequencies ranging from the deep bass around 20 Hz (cycles per second), that is as much felt as it is heard, to the nearly impossible to hear 15,000 Hz, depending on how well you have treated your ears during life. As noted earlier, the frequency of the electromagnetic field determines whether the radiation is visible to the eye. Again, this periodic variation in the electric field takes place in time. Just as it is possible to speak about variation of electrical waves and sound with time, in optics, variations in space can be expressed as **spatial frequencies**. These are usually expressed in cycles/mm (or mm^{-1}). They indicate the rapidity with which an object or image varies in space instead of time. An example that shows a number of spatial frequencies is given in **Fig. 0.39.**

As in the case of many sounds and electrical signals, most spatially repetitive patterns do not consist of a single frequency, but as a musical chord, are made up of some fundamental frequency plus its overtones, or higher harmonics. The discussion of spatial frequencies in optics is based on some interesting, but relatively complicated mathematics. You may want to read this section once to get the general ideas, then come back later after you have done **Project #10**. Certainly, here is a case where hands-on work will improve your understanding of the discussion of the subject.

An example of an object with a few spatial frequencies is the diffraction grating. If the grating just discussed consisted of a sinusoidal variation, as shown in **Fig. 0.40(a)**, there would only be a zero order and the first

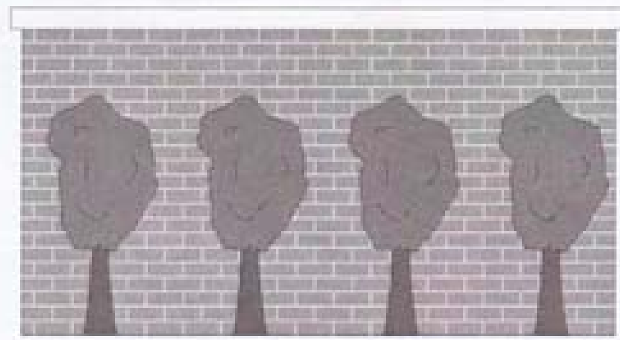


Figure 0.39. Spatial frequencies in an object.

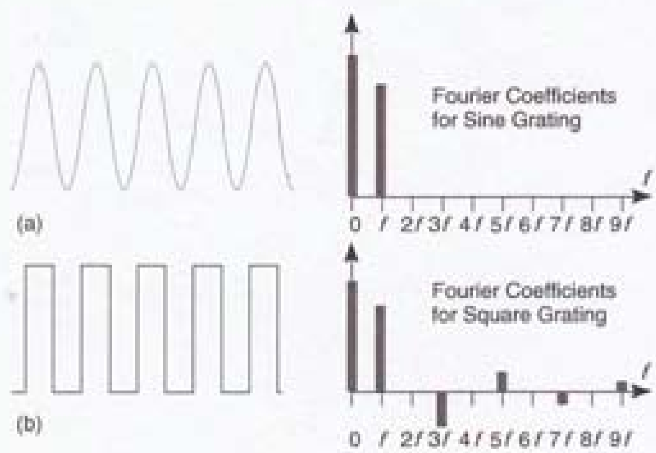


Figure 0.40. Sinusoidal grating versus black and white grating (Fourier analysis).

orders ($m = \pm1$). As repetitive patterns depart from sinusoidal, additional diffraction orders appear and in the case of the black and white grating, a whole series of diffraction orders are present **(Fig. 0.40(b))**.

All of this can be expressed mathematically in terms of **Fourier (Four-ee-ay) Theory**. We will not go into the mathematical expression of the theory, but only graphically express the result as simply as possible.

Any periodic (repeating) function can be expressed as a series of sine and cosine functions consisting of the fundamental periodic frequency (f) and its higher harmonics (those frequencies that are multiples of the fundamental frequency, f ($2f$, $3f$, $4f$, ...) The amount that each frequency contributes to the original function can be calculated using some standard integral calculus expressions. The decomposition of the periodic pattern into its harmonics is referred to as **Fourier Analysis**. This analysis determines the amplitude of each harmonic contribution to the original function and its phase relative to the fundamental (in phase or 180° out of phase).

The procedure can be, in a sense, reversed. If a pattern at the fundamental frequency is combined with the appropriate amounts of the higher harmonics, it is possible to approximate any function with a repetition frequency of the fundamental. This is referred to as **Fourier Synthesis**. To completely synthesize a function such as our example of an alternating black and white grating, an infinite number of harmonics would be needed. If only frequencies up to some specific value are used, the synthesized function will resemble the function, but it will have edges that are not as sharp as the original. A simple example **(Fig. 0.41)** using only a fundamental and two harmonics shows the beginning of the synthesis of a square wave function, similar to our black and white grating. What you will be investigating in **Project #10** are optical techniques that use Fourier analysis and synthesis in creating images.

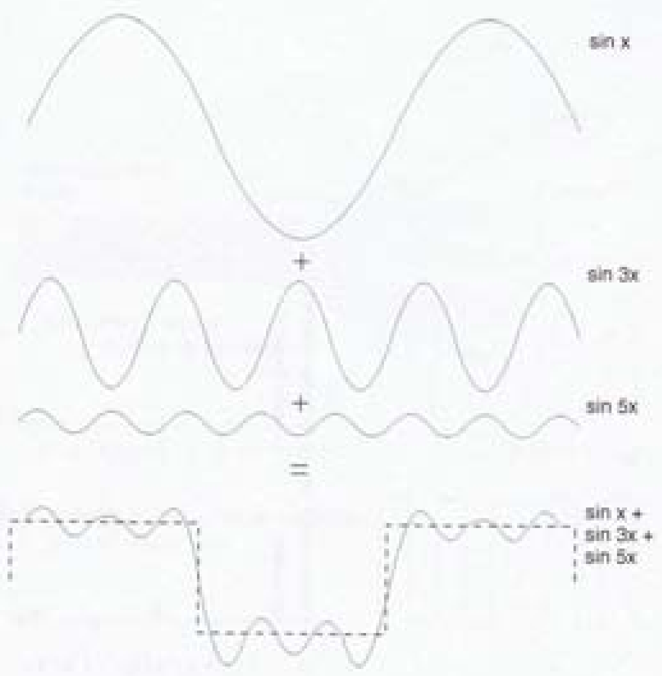


Figure 0.41. Fourier synthesis.

0.7.2 Image Formation

If the black and white grating is illuminated with plane waves of monochromatic light, a number of diffraction orders will be generated by the grating. These plane wave beams diffracted at different angles given by Eq. 0-39, can be focused with a lens located behind the diffraction grating, as shown in **Fig. 0.42**. The focused spots have intensities that are proportional to the square of the amplitudes that we could calculate for this diffraction grating. In effect, the laser plus lens combination serves as an optical Fourier analyzer for a diffractive object.

When a laser beam illuminates a grating, the light will diffract and the spectrum of spatial frequencies will be displayed in the back focal plane of the lens. It turns out that even if the object is not a grating or a series of lines with a number of repetitive spacings, the light pattern in the back focal plane still describes the content of spatial frequencies found in the object. Objects that are large and smoothly varying in their shading represent low spatial frequencies and will not diffract the beam much. Their contributions, therefore, lay close to the optical axis of the lens. Objects that are small or have fine detail and sharp edges will cause substantial diffraction and their contributions will be found further from the optical axis in the back focal plane of the lens.

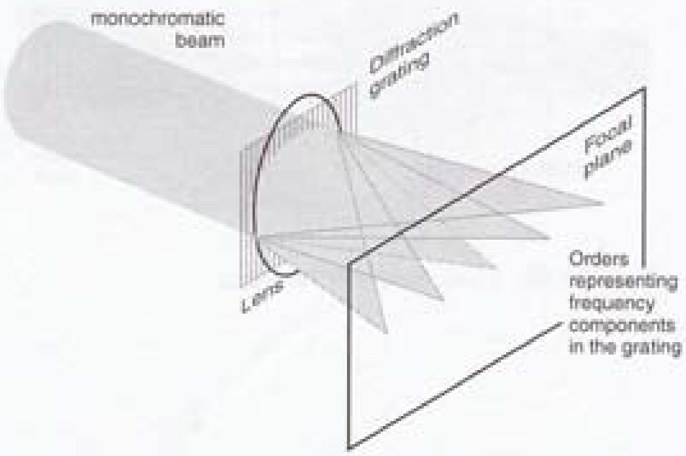


Figure 0.42. Optical Fourier analysis.

Suppose as an object we use a fine, square mesh wire screen. This is a pair of crossed gratings only coarser than the diffraction grating just discussed earlier (**Fig. 0.42**). When this square grating is illuminated by a laser beam, the diffraction orders are focused to a series of spots at the back of the focal plane of the lens and the spatial frequencies form a two-dimensional grid of points. The separation between the points is determined by the distance between neighboring wires, representing the grating constant for this coarse grating.

If the lens is more than one focal length from the grating, then somewhere beyond the Fourier transform plane, a real image of the grating will be formed. The geometry is shown in **Fig. 0.43**. The interesting point of this arrangement is that the image can be understood as a light distribution that arises out of the interference of the light from the spatial frequency components of the object located at the back focal plane of the lens. In other words, the image is a Fourier synthesis of the the spatial frequencies in the grating.

This imaging can be thought of as a two step process: Fourier analysis followed by Fourier synthesis. This approach to analyzing images was first proposed by Ernst Abbe, a lecturer at the University of Jena, who was hired by Carl Zeiss to understand and design microscope lenses. After some study one sees that the larger the collection angle of an imaging lens, the higher the possible resolution, since the higher spatial frequency components appear farther from the axis. Although very little light is collected near the edge of the lens, it is this light that contributes to the fine detail in high resolution images.

0.7.3 Spatial Filtering

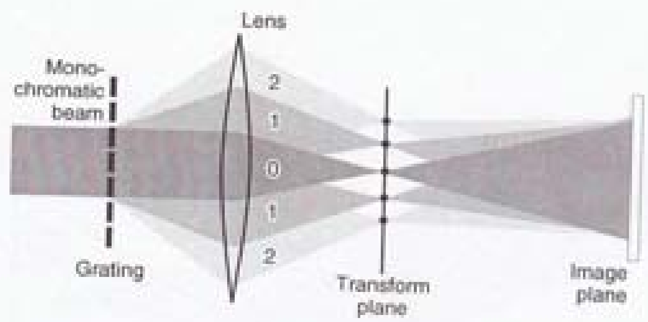


Figure 0.43. Abbe theory of imaging.

Since the light in the Fourier transform plane (**Fig 0.43**) is arranged according to increasing spatial frequency with radius, then any intervention in that plane in the form of a mask will change the distribution of spatial frequencies in the plane. It will also change the content of the image, but in a very predictable way.

The procedure of modifying an image by "changing" the spatial frequencies contained in it is called **spatial filtering**. One example of such a procedure is the spatial filtering of a transparency of a picture of a television screen. The Fourier transform of the picture is a rather raggedy-looking patch at the center of the picture and a series of equally spaced dots arranged in a vertical line. These dots represent a periodic, grating-like feature in the picture. This grating is due to the series of parallel lines, called a **raster**, that is used to build up an image on the TV screen. The electron beam that writes on the face of the tube in a TV set does so as a series of parallel lines. By turning the beam on and off as it is swept across the screen and dropping down a little on each sweep, the circuitry builds up a picture on the tube. If you look at a TV screen up close you can see the raster. If the dots represent the raster, where is the rest of the image? It resides in the raggedy-looking patch at the center of the beam. This analysis and synthesis process of imagery will be demonstrated as one of the experiments in **Project #10**.

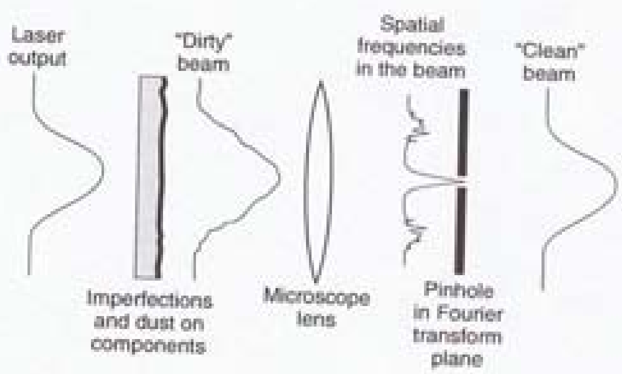


Figure 0.44. Spatial filtering.

There are a number of applications that are based on this approach to imaging. One of these "cleans up" a laser beam. The irradiance distribution of the beam in many lasers is Gaussian (Section 0.6.1) as it exits the output mirror of the laser. However, dust and small imperfections in the lenses, windows, and surfaces that it traverses or reflects from can produce irregularities in the irradiance pattern. The Gaussian distribution represents a low frequency spatial variation in the beam, whereas the irregularities contain higher spatial frequencies. When the laser beam is focused with a microscope objective, as shown in **Fig. 0.44**, these variations are arranged according to their spatial frequencies. If a small pinhole, whose diameter is sufficiently large to pass the low frequency Gaussian portion of the beam and block the high frequency part, the irregularities will be removed from emerging beam and a "clean" laser beam will result.

Another application involves the use of spatial frequencies for object recognition. In some areas of photographic surveys, the amount of data to be analyzed is enormous. Provided a feature of interest has some particular set of spatial frequencies connected with it (spacing between ties in the case of railroads, for example), the laser and lens combination can be used to recognize the possible presence of these features in the photograph. Other applications include inspection of products, such as the tips of hypodermic needles. The average spatial frequency pattern for a large number of good needles is stored in a computer memory. Then the pattern of each new tip is compared to it. Those needles that do not fit the stored pattern to within certain criteria are then rejected. Since the actual position of the tip does not affect the spatial frequency pattern, the test is insensitive to location errors, whereas a direct inspection of the image of the needle tip would have to locate it with a high degree of precision.

0.8 References

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Component Assemblies

All ten experiments use a number of similar component assemblies. In order to simplify the experimental set up procedure we have included a section on building these assemblies. This components section contains drawings of each assembly and easy to understand instructions.

The parts are labeled with a single letter in the instructions. The Newport catalog number that appears on some of the items is listed next to the part label. The catalog numbers in parentheses denote metric versions of the same item.

Alignment of Components

All assemblies, except the lens chuck assembly (LCA), are intended to be screwed directly into the rectangular lab bench (sometimes referred to as an optical breadboard, since it can be used to set up optical systems on an experimental basis). Alignment of many of the components is made simpler by directing the optical paths along the screw holes on the surface. To adjust the height or alignment of a component, rotate the assembly in the post holder and reposition the post within the holder.

In a number of the later experiments, you will notice that there are some standard assemblies in the same locations. One particular geometry that is used for all experiments after Project #3, has a U-shaped form: One arm consists of a laser assembly (LA) and beam steering assembly (BSA-I). The side of the "U" is between this BSA-I and a second BSA-1. In some experiments a laser beam expander, described and constructed in Project #3, is located within the arm between the two beam steering assemblies. The third arm consists of any number of components that are specific to the particular experiment. If the experiments are being done in order, then it should be possible to construct the basic U-shaped geometry, LA plus two BSA-I's, and conduct the balance of the experiments without having to tear down after each set of experiments.

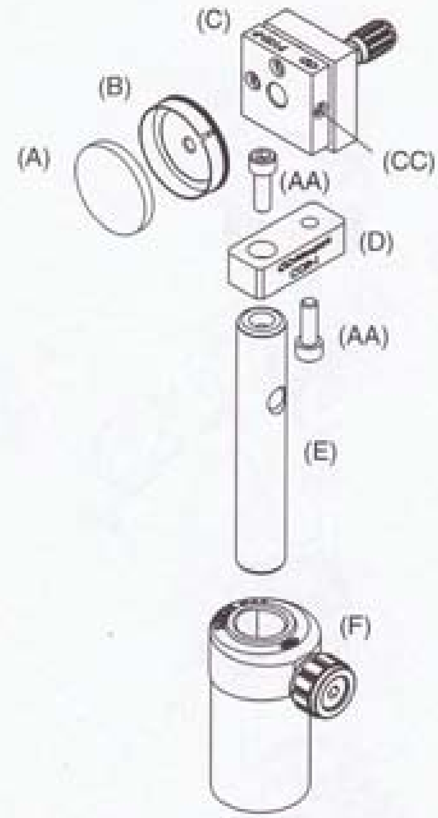
A Note on Handling Optics

When handling optical components treat the optical surfaces of lenses and mirrors with care. Never touch those surfaces. If there are lens tissues or finger cots available, use them to protect the surfaces from finger oils and contamination. If not, handle the components by their edges. Assemble components over a table surface. (Do not lift components any higher off the table than necessary)

Beam Steering Assembly: (BSA-I)

This assembly consists of:

Part	Cat # (Metric #)	Qty	Description
A	10D20ER.1	1	Mirror 1 inch
B	UPA1	1	Mirror holder
C	P100-A (M-P100-A)	1	Mirror mount,adj
D	COR-1	1	Center of rotation bar
E	SP-3 (M-SP-3)	1	Post, 3 inches
F	VPH-2 (M-VHP-2)	1	Post holder, 2 inches
AA	8-32 (M4)	2	Socket hd screws
BB	¼-20 (M6)	1	Socket hd screws
CC	8-32 (M4)	1	Set screw



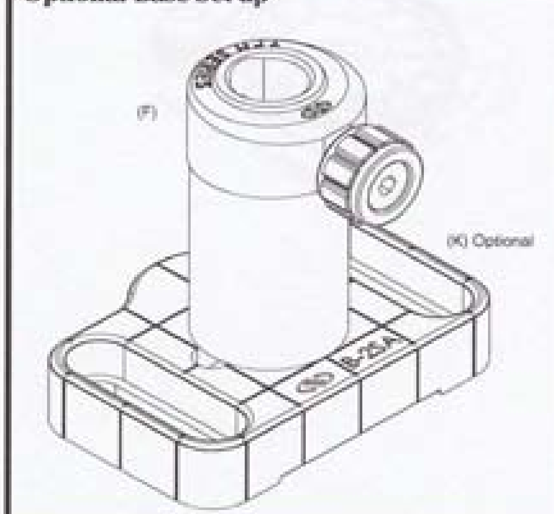
1. Place the 1 inch mirror (A) into its holder (B). If the mirror seems to be stuck, place several sheets of lens tissue on the table and gently lay the holder (B) and mirror (A) on the table with the mirror is facing down. Push straight down until the mirror bottoms out in the holder.

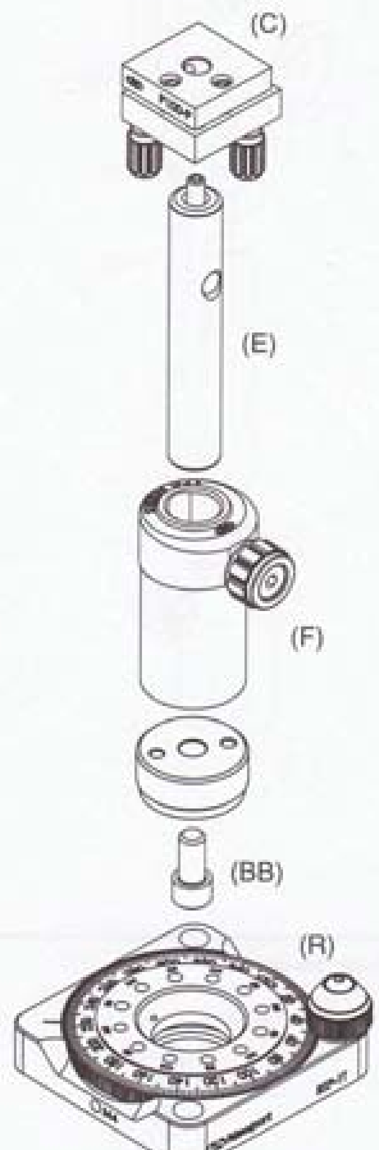
   Do not move the mirror side to side or severe damage to the mirror coating could result.

2. Put the mirror holder (B) into the adjustable mirror mount (C). Secure the mirror holder (B) into the mount (C) using the set screw (CC) in its side. Do not tighten more than finger tight.
3. Use one of the two 8-32 socket head cap screws (AA) to bolt the bar (D) that locates the edge of the mirror over the center of the post (E). You may need to remove the 8-32 set screw that comes shipped with the post (E) first. Save this screw.
4. Use the second 8-32 socket head cap screw (AA) to bolt the mirror assembly (A-B-C) to the other hole in the bar (D).
5. Insert a ¼-20 socket head cap screw (BB) into the post holder (F) from the inside, place the holder over the hole in the optical breadboard where the assembly is to be located and tighten until the screw bottoms out in the holder (F).
6. Place the post assembly (A-B-C-D-E) in the holder (F) and tighten the side screw sufficiently to hold the unit together.

NOTE: For some assemblies, the post holder (F) is not attached directly to the breadboard. Instead the cap screw (BB) is inserted through a base plate (K) from the bottom. This gives the assembly a base and allows it to be moved around in the table.

Optional Base Set-up





Modified Beam Steering Assembly: (BSA-II)

This assembly consists of:

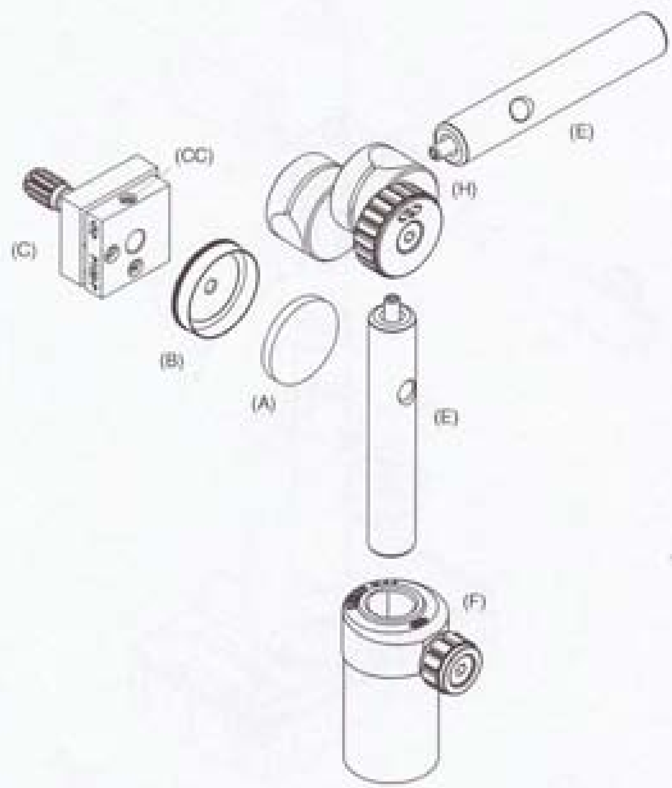
Part	Cat # (Metric #)	Qty	Description
C	P100-P (M-P100-1)	1	Mirror mount
E	SP-3 (M-SP-3)	1	Post, 3 inches
F	VPH-2 (M-VHP-2)	1	Post holder, 2 inches
R	RSP-1T	1	Rotation Stage
BB	¼-20 (M6)	1	Socket head screws
CC	8-32 (M4)	1	Set screw

This modified version of this beam steering assembly (BSA-II) consists of an adjustable mirror mount (C) whose surface (adjustment knob side) is mounted perpendicular to the post (E) with a 8-32 set screw (CC) as shown in the inset. The post holder is attached to the center plug in the rotation stage (R).

Modified Beam Steering Assembly: (BSA-III)

This assembly consists of:

Part	Cat # (Metric #)	Qty	Description
A	10D20ER.1	1	Mirror 1 inch
B	UPA1	1	Mirror holder
C	P100-P (M-P100-P)	1	Mirror mount,adj
E	SP-3 (M-SP-3)	2	Post, 3 inches
F	VPH-2 (M-VHP-2)	1	Post holder, 2 inches
H	CA-2	1	Variable angle holder
BB	¼-20 (M6)	1	Socket hd screws
CC	8-32 (M4)	1	Set screw
DD	8-32 (M4)	1	Set screw

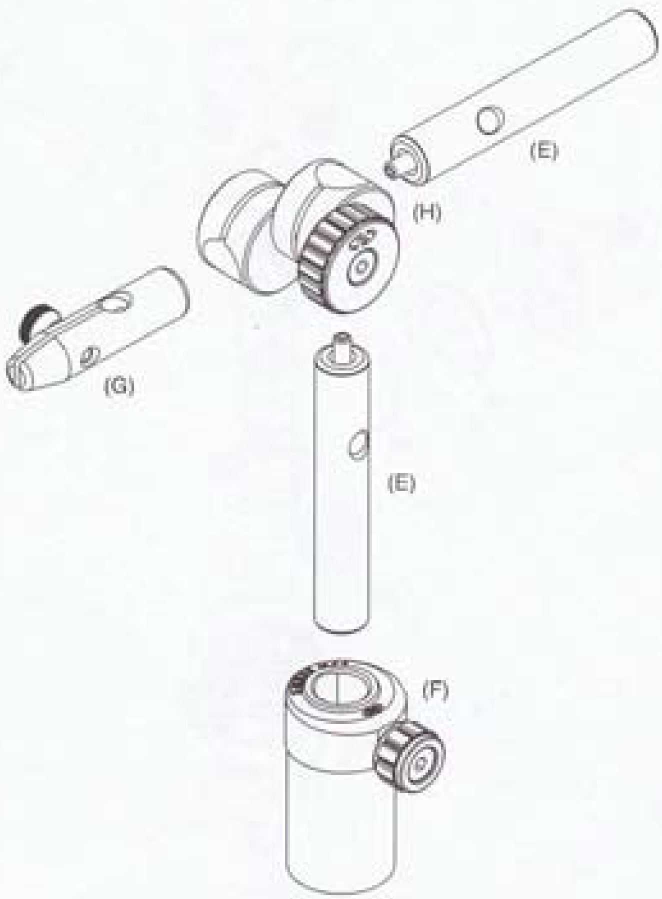


1. Place the 1 inch mirror (A) into its holder (B). If the mirror seems to be stuck, place several sheets of lens tissue on the table and gently lay the holder (B) and mirror (A) on the table with the mirror is facing down. Push straight down until the mirror bottoms out in the holder.

   Do not move the mirror side to side or severe damage to the mirror coating could result.

2. Put the mirror holder (B) into the adjustable mirror mount (C). Secure the mirror holder (B) into the mount (C) using the set screw (CC) in its side. Do not tighten more than finger tight.
3. Insert the 8-32 set screw (DD) into one end of the post (E). Screw the mirror mount (C) onto this 8-32 set screw.
4. Insert this mirror mount-post combination (E-A-B-C) into the variable angle holder (H) in the hole **farthest** from the tightening knob. Insert a second post (E) into the remaining hole in the variable angle holder (H). Lightly tighten the knob to hold the two posts in place.
5. Insert a ¼-20 socket head cap screw (BB) into the post holder (F) from the inside, place the holder over the hole in the optical breadboard where the assembly is to be located and tighten until the screw bottoms out in the holder (F).
6. Insert the post assembly (E-A-B-C-H-E) into the post holder (F) and lightly tighten the thumb screw to hold the assembly together.

This version of the beam steering assembly is intended to be located in one place and target movement is done by changing the length and direction of the posts (E) in the variable angle holder (H).



Target Assembly (TA-I)

This assembly consists of:

Part	Cat # (Metric #)	Qty	Description
E	SP-3 (M-SP-3)	2	Post, 3 inches
F	VPH-2 (M-VPH-2)	1	Post holder, 2 inches
G	FC-1 (M-FC-1)	1	Filter holder
H	CA-2	1	Variable angle holder
BB	¼-20 (M6)	1	Socket head screw
DD	8-32 (M4)	1	Set screw

1. Insert the 8-32 set screw (DD) into one end of the post (E). Screw the filter holder (G) onto this 8-32 set screw.
2. Insert this filter holder-post combination (E-G) into the variable angle holder (H) in the hole **farthest** from the tightening knob. Insert a second post (E) into the remaining hole in the variable angle holder (H). Lightly tighten the knob to hold the two posts in place.
3. Insert a ¼-20 socket head cap screw (BB) into the post holder (F) from the inside, place the holder over the hole in the optical breadboard where the assembly is to be located and tighten until the screw bottoms out in the holder (F).
4. Insert the post assembly (E-G-H-E) into the post holder (F) and lightly tighten the thumb screw to hold the assembly together.

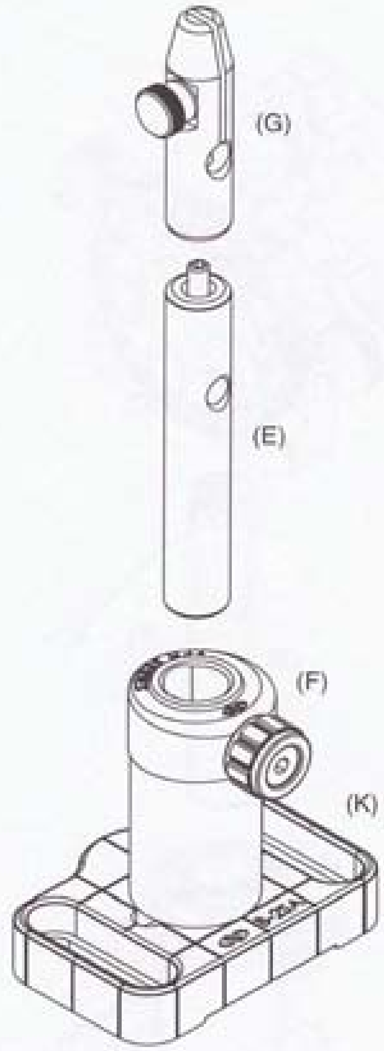
This version of the target assembly is intended to be located in one place and target movement is done by changing the length and direction of the posts (E) in the variable angle holder (H).

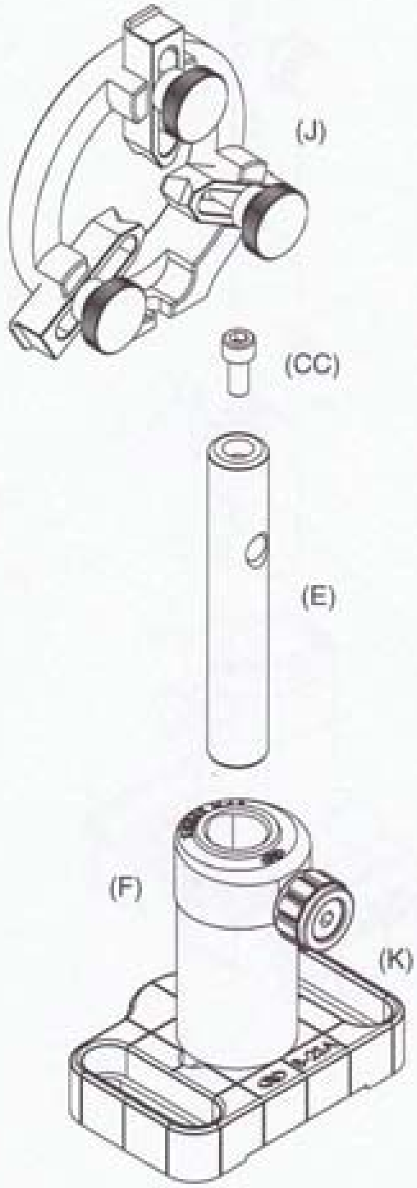
Modified Target Assembly (TA-II)

This assembly consists of:

Part	Cat # (Metric #)	Qty	Description
E	SP-3 (M-SP-3)	1	Post, 3 inches
F	VPH-2 (M-VPH-2)	1	Post holder, 2 inches
G	FC-1 (M-FC-1)	1	Filter holder
K	B-2SA	1	Base plate
BB	¼-20 (M6)	1	Socket head screw
DD	¼-20 (M6)	1	Set screw

A modified assembly does not use the variable angle holder (H) and consists of the filter-post combination (E-G) mounted directly into the post holder (F) and base plate (K) with the ¼-20 socket head screw (BB). This assembly is not intended to be screwed into the optical bench, but moved around on the base plate (K).





Lens Chuck Assembly (LCA)

This assembly consists of:

Part	Cat # (Metric #)	Qty	Description
E	SP-3 (M-SP-3)	1	Post, 3 inches
F	VPH-2 (M-VPH-2)	1	Post holder, 2 inches
J	AC-1A	1	Lens chuck
K	B-2SA	1	Base plate
BB	¼-20 (M6)	1	Socket head screw
CC	8-32 (M4)	1	Set screw

1. Insert the set screw (CC) into the base of the lens chuck (J).
2. Screw the post (E) onto the set screw (CC) in the base of the lens chuck (J). Tighten the post firmly.
3. Place the holder (F) over the center hole in the base plate (K), insert a ¼-20 screw through the baseplate (K) and tighten until the screw bottoms in the holder (F).
4. Insert the lens chuck-post combination (E-J) into the post holder (F) and tighten the thumb screw to hold the assembly together.

This assembly is not intended to be bolted into the optical bench, but moved around on the table.

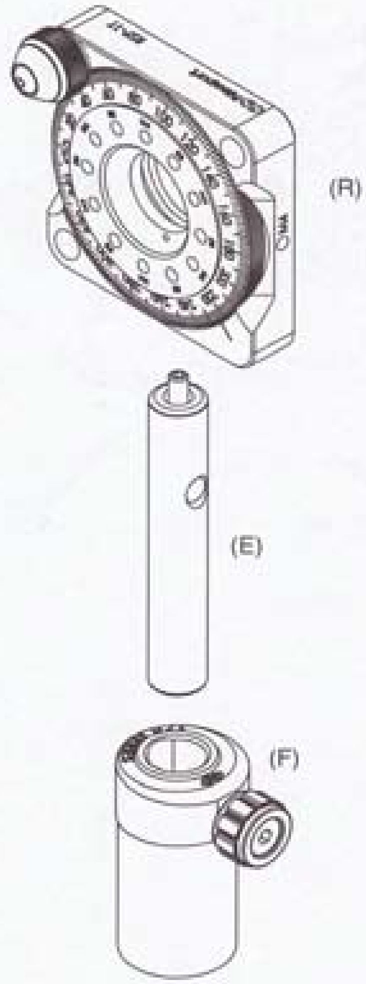
Rotational Stage Assembly (RSA-I)

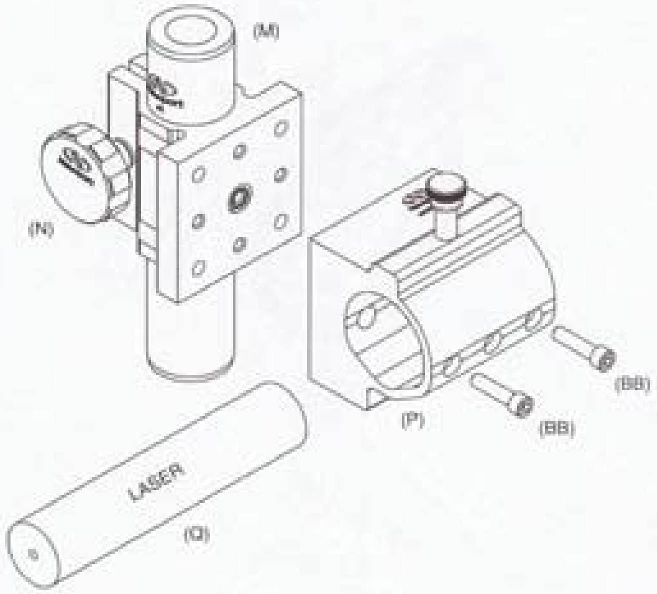
This assembly consists of:

Part	Cat # (Metric #)	Qty	Description
E	SP-3 (M-SP-3)	1	Post, 3 inches
F	VPH-2 (M-VPH-2)	1	Post holder, 2 inches
R	RSP-1T	1	Rotation stage
BB	¼-20 (M6)	1	Socket head screw
CC	8-32 (M4)	1	Set screw

This assembly will be used in two slightly different versions. The type RSA-I will be have the rotation stage (R) mounted such that the 1 inch clear aperture is perpendicular to the table surface.

1. Insert the set screw (CC) into the post (E). Leave approximately ¼ inch protruding from the post.
2. Into one of the holes in the center of the **narrow** side, screw the rotation stage (R) onto the set screw (CC) in the post (E).
3. Insert a ¼-20 socket head cap screw (BB) into the post holder (F) from the inside, place the holder over the hole in the optical breadboard where the assembly is to be located and tighten until the screw bottoms out in the holder (F).
4. Insert the rotation stage-post assembly (E-R) into the post holder (F) and tighten the thumb screw to hold the assembly in place.





Laser Assembly (LA)

This assembly consists of:

Part	Cat # (Metric #)	Qty	Description
M	41 (M-41)	1	7 inch rod
N	340-RC (M-340-RC)	1	Rod clamp
P	ULM	1	1-¾ in laser mount
Q	R-31005	1	HeNe laser
BB	¼-20 (M6)	2	Socket head screw

Warning

The HeNe laser can cause permanent damage to your vision. Never look directly into the laser tube or at a reflection from a specular surface. Do not wear rings or other shiny jewelry when working with lasers. Use only diffuse (white 3x5 card) reflectors for viewing HeNe laser beam. Protect fellow co-workers from accidental exposure to the laser beam. Always block laser beam close to the laser when the experiment is left unattended.

1. Mount the rod (M) to the breadboard by placing the socket driver into the rod and mounting the rod over one of the tapped holes. Tighten the bolt with the socket driver until the rod is firmly attached to the table.

2. Screw the laser clamp (P) onto the rod clamp (N) with the two ¼-20 socket screws (BB).

3. Slide the laser mount-rod clamp combination (N-P) onto the rod (M) and tighten the large knurled knob on the rod clamp (N).

4. Insert the laser (Q) into the laser mount (P) such that approximately 3 inches protrudes from either side of the clamp. Rotate the laser (Q) until the alignment mark on the front of the laser is up and gently tighten the set screw in the laser clamp to hold the laser. **Do not over tighten or the laser could be damaged.**

4. The laser supplied with the Newport Optics Education Kit is equipped with an internal shutter. The shutter is opened and closed by inserting a flat-bladed screw driver into the slot above the laser output aperture. Rotate the screw driver clockwise to close and counterclockwise to open (the laser is shipped with the shutter in the closed position).

Project #1

The Law of Geometrical Optics:

All optical designs are based upon two very simple laws of optics: the laws of reflection and refraction. Any analysis of an optical system, no matter how elaborate, is done using these two laws to simulate the passage of light rays through the lenses and windows and off the mirrors that make up the optical device. So, the basis of almost everything you will do in optics begins with these two simple laws. It is, therefore, appropriate that the first experiment in this manual is a demonstration of these laws.

The first thing that you will do is to verify the law of reflection: "the angle of reflection equals the angle of incidence". Then you will verify the law of refraction, also known as Snell's Law, which states that "the product of the refractive index of a medium and the sine of the angle of incidence of a ray on one side of an interface between two optical media is equal to the product of the refractive index times the sine of the transmitted ray on the other side of the interface." This can be stated mathematically by,

$$n_i \sin\theta_i = n_t \sin\theta_t \qquad (1\text{-}1)$$

where n_i is the refractive index in the incident medium, θ_i is the angle between the local normal to the interface and direction of the incident ray, n_t is the refractive index in the transmitted medium, and θ_t is the angle between the local normal and direction of the transmitted ray. These angles are measured between the ray and the normal to the surface where the ray hits the interface. The direction of the normal changes on curved surfaces, such as those on a lens or curved mirror, so the normal is sometimes called the **local normal**, since it applies only at that point on the surface and not to neighboring points.

In addition to verifying the basic laws of geometrical optics, this first experiment will also familiarize the student with the "tools of the trade", the components that make up the experimental set up. The labels placed on the items are the same as those used in the component assembly section.

Newport Equipment Required:

Part	Qty	Description
LA	1	Laser Assembly
BSA-I	2	Beam Steering Assy
BSA-II	1	Beam Steering Assy
BSA-III	1	Beam Steering Assy
TA-I	1	Target Assembly
RSP-1T	1	Rotation stage
05BR08	1	Prism
16569-01	1	Clear plastic tank

Additional Equipment Required:

Part	Qty	Description
QI	1	Index card
QW	1	Metric ruler or meterstick

Table 1.1 - Required Equipment

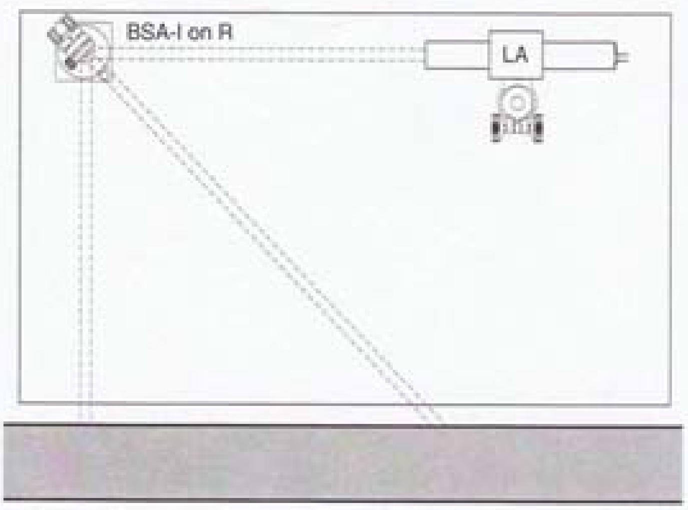


Figure 1-1. Schematic view of Project #1, Law of Reflection.

1.2 The Law of Reflection

A Note on Taking Data

The measurement and recording of data for these projects are as important as the effects you will be exploring. It is only by measuring the size of the effect and checking it with the expressions given in the text, that the subject under discussion can be truly understood. Until the data are analyzed the project is a nice demonstration of an optical effect and not an experiment in optics.

Data should be taken in a standard, bound laboratory record book, if it is available. Recording should be as neat as possible. If something is recorded incorrectly, it should be lined out with a single line and the correct value recorded next to it. Do not erase any data that you record. When there is sufficient data and a reasonable range of data, it should be plotted in the most useful manner. Your instructor can help you determine this.

The law of reflection will be verified by showing that the angle through which a beam reflected by a mirror (angle of incidence plus angle of reflection) is twice the angle made by the beam incident and the normal to the mirror surface (angle of incidence). By scanning the angle of incidence at which the He-Ne laser beam strikes the mirror you will be able to show that the total angle through which the beam is reflected is twice that angle.

1.3 Experimental Set Up

1. The optical breadboard should be located on a table near a wall or the side of a cabinet. Tape a sheet of paper on the wall or cabinet at the same height at which you will set the laser in the next step.
2. Mount a He-Ne laser as described in the Laser Assembly (LA) section of the Component Assemblies Section and place it at the rear of the breadboard.
3. Mount a Beam Steering Assembly (BSA-I) onto a Rotation Stage (R). The Rotation Stage (R) is then attached to the table with ¼-20 screws. The BSA-I should be located such that the incident laser beam is parallel to a nearby wall, as shown in **Fig. 1-1**.

4. Adjust the beam steering mirror to reflect the laser beam back onto itself. Record the position of the rotation stage θ_o in your laboratory notebook or lab sheet.

   EXTREME CARE SHOULD BE USED TO AVOID ACCIDENTAL EXPOSURE OF CO-WORKERS WHEN DIRECTING THE LASER BEAM OUTSIDE OF THE OPTICAL TABLE AREA.

5. Scan the angle of the mirror by turning (R) such that the laser beam is reflected onto the piece of paper on the wall. Record the new angle θ in your notebook and on the sheet of paper on the wall just above the mark locating the center of the beam. Do this for a number of different rotation stage angles that produce beam positions separated by an inch or more on the wall.

6. Measure the perpendicular distance Y from the mirror to the wall and the distance X from that point on the wall to the marks on the wall as shown in **Fig. 1-2**. Use your knowledge of the definitions of the trigonometric functions and a calculator to determine the angle between the laser beam direction and the reflected beam direction using the distance measurements you have just made. Record your calculations and these angles next to those for the incidence angles.

7. Compare the total reflected angles θr to the incident angles $(\theta - \theta_o)$. You should find that the total beam deviation angle is twice the angle of incidence, confirming the law of reflection.

A Note on Mirror Mounts

All of the beam movement in this part of the experiment was done using the rotation stage (R). However, you can also move the beam using the knobs on the adjustable mount (C). Note that one knob moves the beam horizontally and the other vertically. Not all adjustable mounts move the beam in two directions perpendicular to each other. Those mounts that do are called orthogonal mounts, because the movements are at right angles, or orthogonal, to each other. It is much easier to locate a beam with such adjustments. Examine the mount and see if you can understand how its design provides this feature.

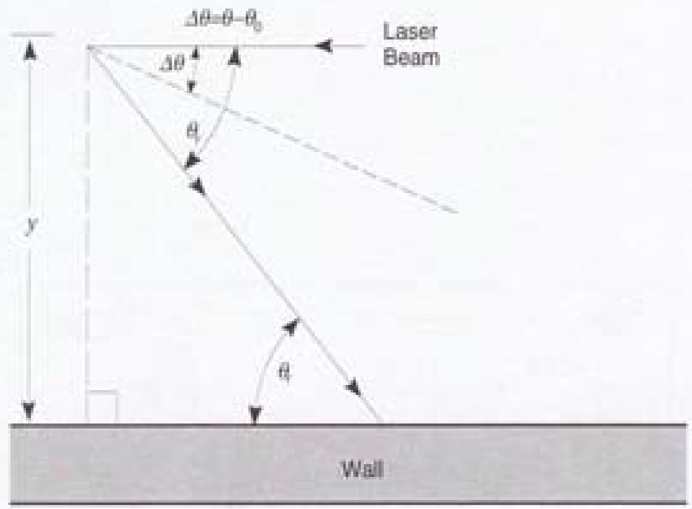


Figure 1-2. Geometry for calculating incident and beam deflection angles.

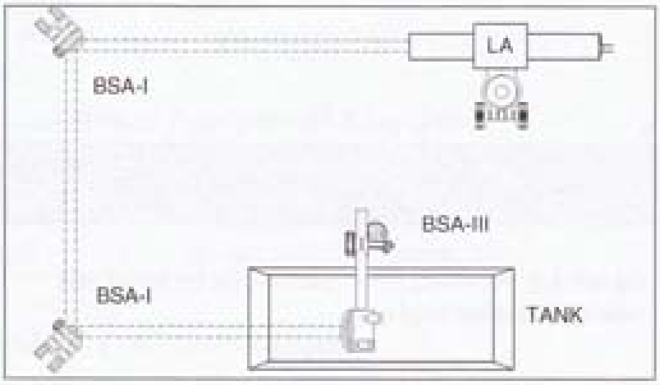


Figure 1-3. Schematic view of Project #1, Law of refraction.

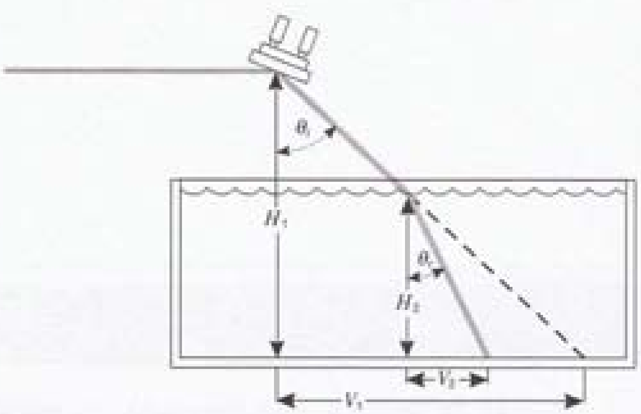


Figure 1-4. Measurements to determine the refractive index of a liquid.

The Law of Refraction

The verification of the law of refraction will be shown by measuring the incident and transmitted angles of a He-Ne laser beam incident upon an air-water interface.

Experimental Set Up

1. Mount a laser assembly (LA) along the edge of the breadboard with the beam parallel to the edge of the board, as shown in **Fig. 1.3.** Set the laser using the adjustable rod clamp (S) at the maximum height above the breadboard surface.
2. Mount two beam steering assemblies (BSA-1) at the corners of the optical breadboard, as shown in **Fig 1.3**.
3. Mount a Modified Beam Steering Assembly (BSA-III) described in the Components Assembly Section. Locate the post holder (F) off the beam axis, so that the mirror is in line with the laser beam. Rotate the mirror to direct the laser beam approximately at an angle of 45 degrees to the breadboard surface.
4. Measure the perpendicular distance from where the laser intersects the mirror (H_1 in **Fig. 1.4**) to the bottom of the plastic box. Measure the distance from this point to where the laser beam strikes the bottom of the plastic box (V_1 in **Fig. 1.4**). Fill the plastic box with clear water to within 1 cm of the top.
5. In the same manner as in step #4 measure the perpendicular distance from the point where the laser beam enters the water's surface to the bottom of the box (H_2 in **Fig. 1.4**) and from this point on the bottom of the plastic box to where the laser beam strikes the bottom of the plastic box. (V_2 in **Fig. 1.4**)
6. You can now calculate the incident and refracted angles of the beam in water. Using **Eq. 1-1** given above and the fact that the refractive index of air is 1.0, find the sines of the angles and determine the refractive index of water. Your value should be close to 1.33. If not, you might want to check your measurements and calculations. Be sure the distances that you measured are the distances described above.

Additional Experiments

If there are other liquids available that can fill the tank, you can measure their refractive index also. You can check your answer in reference tables of refractive indices in standard handbooks.

#1 – Measurement of Refractive Index of a Transparent Solid using Total Internal Reflection

The phenomenon of total internal reflection (**TIR**) discussed in the Primer will be used to determine the refractive index of a prism. The geometry is somewhat tricky, but it permits the determination of the refractive index of a standard 45°-45°-90° prism without resorting to any damage to the prism.

As pointed out in the Primer, the angle of incidence at which an interface switches from transmitting some light and then to total internal reflection is called the critical angle, θ_c. At this angle where the transmitted ray is traveling along the boundary of an air-glass interface, the transmitted angle is 90°. The critical angle is related to the refractive index of the material n as

$$\sin \theta_c = 1/n.$$

In the case of the experiment you are about to do, things are a little more complicated, but not much. Instead of a single interface to worry about there are two. The first of the interfaces does not involve TIR. It is by rotating a prism until TIR occurs at the second interface and measuring the angle β between an unrefracted beam and the beam at the critical angle that we can determine the refractive index of the prism from an equation whose proof is left as a challenge to the student.

$$n^2 = \sin^2\theta_0 + (\sqrt{2}+\sin\theta_0)^2 \qquad (1\text{-}2)$$

Where θ_0 is related to the angle β through which the beam is deviated by

$$\theta_0 = \beta - 45°. \qquad (1\text{-}3)$$

Experimental set up

1. Mount the laser assembly (LA) along the rear edge of the breadboard with the output toward a nearby wall. Mount a beam steering assembly that has been modified to place the mirror mount parallel to the table surface (BSA-II in the Component Assembly Section) onto the center of a rotation stage (R). The laser beam should be 4 to 5 mm higher than the BSA-II and parallel to the table surface. Tape a piece of paper on the wall.

   Place a 1 inch round mirror flat against the wall and adjust the angle of the laser such that the beam is retro-reflected on itself. This assures the beam is at a right angle to the wall for our calculations. Remove the mirror and mark the position of the laser beam on the paper taped to the wall. This represents the undeviated beam.

2. Place the prism such that the laser beam is incident to one of the short sides as shown in **Fig. 1-5.** Retro-reflect the laser beam back to the laser head. You may need to adjust the angle screws of the mount on which the prism is sitting. The center of the prism hypotenuse should be over the center of rotation. Measure the distance from the center of rotation of the prism to the wall.

3. Rotate the prism clock-wise by turning the rotation stage (R) until the laser beam just exits the hypotenuse of the prism and strikes the wall. Do this several times until you feel that you are at the transition at which light just begins to be transmitted out the hypotenuse. The measurement of θ_c is given by $\tan(\theta_c + 45°) = Y/X$, where X is the distance from the interface to the wall and Y is the distance from the location of the beam at the critical angle to the point where the beam hits the wall before the prism is placed in the beam.

4. Substitute this calculation into the formula given above and compare this value (1.517) with the published index of BK7 glass at the wavelength of the helium-neon laser.

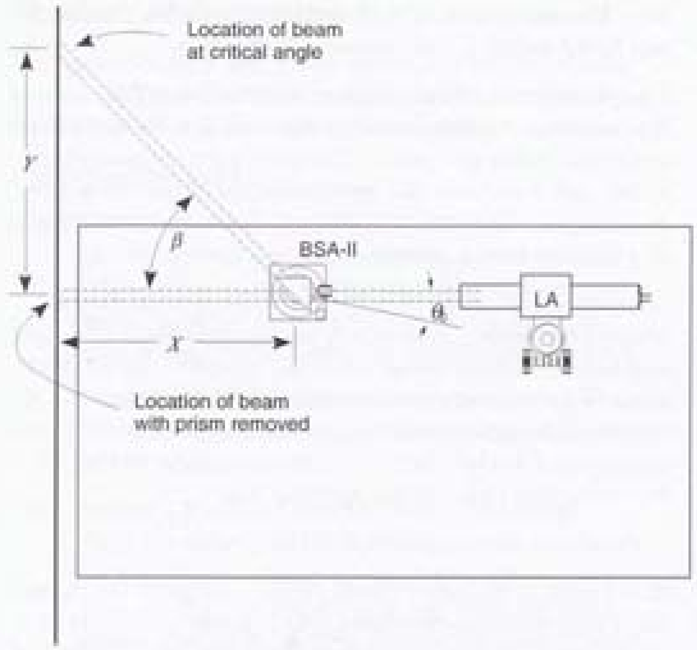


Figure 1-5. Top view refractive index experiment.

This experiment has provided you with the opportunity to use a type of laboratory equipment available in most companies. Later in some projects, the angles and distances are determined and the modular equipment you used here can be replaced by specific optical components and holders machined to the specifications obtained from the experiment. But as long as a project is in an experimental phase, the flexibility of the equipment used here enables engineers to setup rapidly and revise their optical systems.

#2 – Index Gradients

This particular experiment must be prepared ahead of time. Fill the tank with water and add several table spoons of salt to it. Let the tank stand undisturbed overnight. Direct a laser beam along the length of the tank underneath and parallel to the surface. Try this a different heights within the tank. Note that the beam emerges from the tank at a different height than it enters. This is because there is a refractive index gradient in the tank. Index gradients bend light in various locations. They are responsible for mirages and the "wet" appearance of a distant spot on a hot road. Optical technology now depends on small optical components that have index gradients designed into them so that they will act as lenses. They are referred to as GRIN lenses, where the first two letters are taken from "gradient" and the second two are taken from "index."

Project #2
The Thin Lens Equation:

While the idea of creating images with lenses is easy to grasp, understanding of location, magnification and orientation of an image usually comes from working with lenses. This project is more than a verification of the thin lens equation. It is also a study in the sizes and orientations of images and in the effect of combination of lenses and their equivalent focal length.

In this experiment you will apply the Gaussian form of the thin lens equation:

$$1/f = 1/s_o + 1/s_i \qquad (2\text{-}1)$$

to determine the focal length of a lens or a combination of lenses. By careful measurements of object distances (s_o) and image distances (s_i) (**Fig. 2-1**) it is possible to calculate the focal length (f) of an unknown lens to less than a percent of the true focal length. To use this equation requires that the thickness of the lens be small relative to its focal length. If the lens is "too thick", the lens equation breaks down and a more complicated calculation is required to determine the image distance and magnification (see references).

Since a negative lens alone cannot produce a real image, a combination of a positive lens and a negative lens is used to determine the focal length of the negative lens.

The relation between object and image location is taken for granted once you are given the Gaussian form of the thin lens equation. But it is usually forgotten that some approximations have gone into deriving the equation. As a method of rapidly laying out the location and focal lengths of various lenses, it has some use, but as a means of doing optical engineering, it cannot provide the precision required for serious calculations of optical performance. Still, as a means of exploring the nature of imaging, experiments involving the thin lens equation can be most useful.

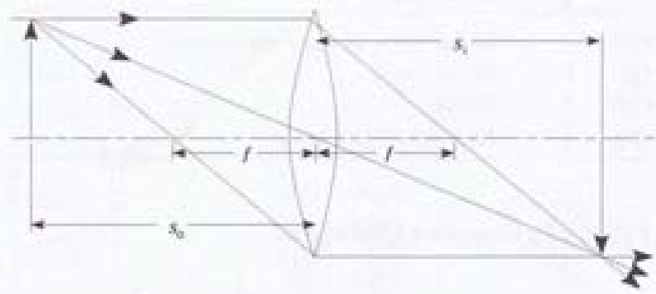


Figure 2-1. Definition of lens parameters.

Newport Equipment Required:

Part	Cat #	Qty	Description
TA-I		1	Target Assembly
TA-II		1	Target Assembly
LCA		2	Lens Chuck Assembly
LKIT-2		1	Lens kit, as noted below
LP1	KPX094	1	100 mm focal length lens
LP2	KPX106	1	200 mm focal length lens
LP3	KPX076	1	25.4 mm focal length lens
LN1	KPC043	1	-25.4 mm focal length lens

Additional Equipment Required:

Part	Qty	Description
QW	1	Meterstick or tape measure
QI	1	Index card
QT	1	Target
QQ	1	High intensity lamp

Table 2.1 - Required Equipment

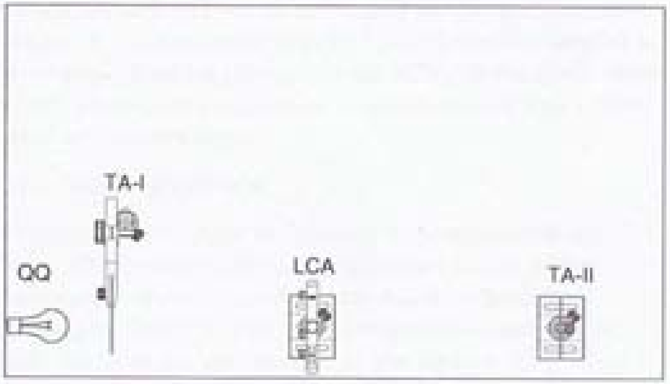


Figure 2-2. Project #2, Positive lens set up.

Experimental Set Up:

1. Construct a target (QT) on an index card by ruling a square grid of lines 5 mm apart. This will serve as your object. You can compare the size of the images you generate to this object to determine the magnification. Add some arrows to enable you to determine if the images are upside down or right side up. Mount this in a target assembly (TA-I) close to the edge of the breadboard (**Fig. 2-2**).

2. Unroll the tape measure along the breadboard edge so that the start of the tape is directly under the target. Place a high intensity lamp approximately 2 inches behind and at the same height as the target.

Positive Lens

3. Read the note on handling lenses in the components assembly section if you have not done so already. Take a positive 100 mm focal length lens from the lens kit and mount it in a lens chuck component assembly (LCA).

4. Place the lens about 125 mm from the target and record in your notebook, the exact distance between the lens and the target. This is the first object distance.

5. Mount the white card in a second target assembly mount (TA-II). Place the TA-II at the end of the breadboard and slowly move it toward the lens until an image is seen. Continue moving the TA-II until the image starts to become blurred. Move it away from the lens until the image is again seen. Move the TA-II to produce the sharpest image and mark this position. The distance from the lens to the card is the image distance. Record this value along with object distance.

6. Mark on the white card two points on the image that represent the distance between a specific number of grid lines and, either now or later, measure the distance between these points. Measure the distance between the corresponding points on the object grid. Record the values in your notebook along with the image and object distances.

7. Redo steps 4 through 6 with the object distance set close to the values of 150, 200, 400, and 600 mm. Record the object and image distances and the distance between two points on the image. This will give you sufficient data to make a good determination of the focal length of the lens.

8. Using the relationship for lens focal length, object distance and image distance, $1/f = 1/s_o + 1/s_i$, calculate the focal length of the lens using each of the sets of data. Find the average of the results and compare this value to that specified in the lens kit. Also calculate the magnification of the image for each object distance from the distances marked and measured on the white card divided by the corresponding distance on QT. Compare these to the ratio of the image distance divided by the object distance. (See **Eq. 0-6** in the Primer.)

9. Return to the first lens placement with an object distance of 125 mm. Verify that the image is located at the point that you recorded it earlier by moving the TA-II into the correct position. Now, keeping the TA-II fixed, move the lens toward it until you get an image on the index card. Measure the new image and object distances and compute the magnification. Do they bear any relation to the earlier measurements?

Negative Lens

Bi-concave lenses have negative focal lengths and the image they form is virtual. Since only image distances for real images can be directly measured, the technique that uses an auxiliary positive lens of known focal length, described in **Section 0.2** of the Primer, is used to determine the focal length of a negative lens.

10. Place a negative focal length lens (LN1) in an LCA with its concave side facing the object and measure the distance from the object to the lens.

11. Next place the positive lens whose focal length you have just measured more than 100 mm beyond the negative lens. Obtain a sharp image and measure the image distance from the positive lens.

12. Since you know the focal length of the positive lens and you have measured the image distance, you can calculate the object distance that would be required for this image distance if only a positive lens were present. The image of the negative lens is the object for the positive lens (Rule #5 in **Section 0.1**). Subtract the calculated object distance for the positive lens from the spacing between the two lenses. This is the image distance for the negative lens and will be negative. See **Fig 0-9** in the Primer to help you visualize this. Recalculate the focal length from the lens formula above (remember to use the correct signs on the image and object distances). Compare this to the value in the lens kit guide.

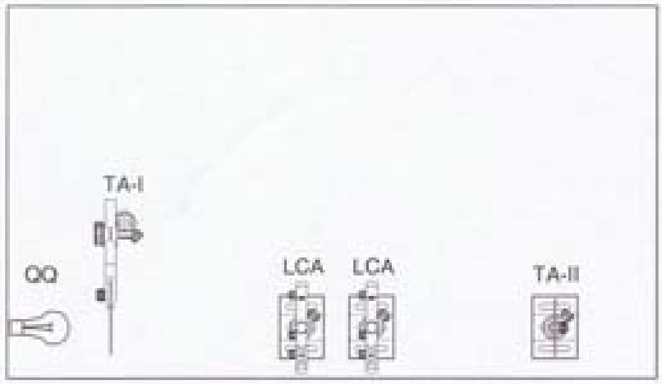


Figure 2-3. Project #2, Negative lens set-up.

Additional experiments:

Combinations of lenses

1. Using a combination of lenses from the lens kit (for example, a 100 mm EFL (LP1) and a 200 mm EFL (LP2)), mount the two lenses next to one another. You might tape the two lenses together at several points near the edges. Do not attach the tape near the center of the lens. Measure the focal length of the combination of lenses as above to find the effective focal length. Compare these results to that calculated using **Eq. 0-8** in the Primer.
2. Repeat the previous step using one positive lens and one negative lens. To assure that you will get a real image you can use a negative lens whose absolute value of the focal length is greater than the focal length of the positive lens. Why is this necessary?
3. Using two LCA's, put the 100mm EFL (LP1) in one and the 25.4 mm EFL (LP3) in the other. Locate LP1 about 200 mm from the object and record the object distance. Locate and record the image distance and orientation. Place LP3 about 60 mm beyond the image location and move the TA-II to find the image for the combination. Record the separation between the lenses and the magnification and orientation of the final image. Note that whereas the first image was inverted, the second image is erect with respect to the original object. Verify your measurements by applying the thin lens equation twice to calculate the locations and magnifications of the intermediate and final images.

Project #3
Expanding Laser Beams:

Many times when a laser is used in an optical system, there is a requirement for either a larger beam or a beam that has a small divergence (doesn't change size over the length of the experiment). In some cases the size of the beam becomes critical, for example; when measuring the distance from the Earth to the Moon, a beam one meter in diameter travels to the Moon where it has expanded to several hundreds of meters in diameter and when the return beam intersects the Earth's surface it is several kilometers in diameter. The signal returned from this expansion is millions of times smaller than the original signal, so that the divergence of a laser beam must be reduced to produce strong, detectable signals. Even in the case of earthbound experiments, higher degrees of collimation are required for many applications including some of the projects in this manual.

As was pointed out in the Primer, the product of the beam waist and the divergence of a lens is a constant:

$$d_o\theta = \frac{4\lambda}{\pi} \qquad (3\text{-}1)$$

Therefore, if we want a more collimated beam, the divergence θ must be reduced and that can only be done by increasing the beam waist. This process cannot be easily done by a single lens. First, the beam must be diverged with a short focal length lens and then the diverging beam is recollimated with a large beam waist and smaller divergence. The arrangement of the lenses are essentially those of an inverted telescope. It is inverted since the light goes in the eyepiece lens (the shorter focal length lens) and comes out the objective lens. The amount of beam expansion, and therefore divergence reduction, is equal to the power of the telescope, which is simply the ratio of the focal lengths of the telescope lenses. Therefore after passage through a beam expander, the divergence should be equal to the old divergence **divided** by the power of the telescope.

This experiment will demonstrate the design of two types of laser beam expanders — the Galilean and the Keplerian. Each has distinct advantages. From these experiments you will gain experience in the alignment of laser beams and components and learn some simple techniques that make the process of alignment much easier.

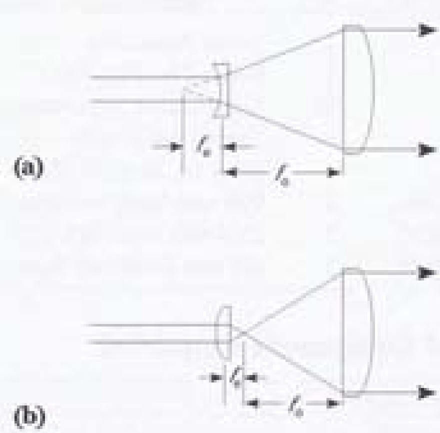


Figure 3-1. Gaussian beam collimation. (a) Galilean telescope. (b) Keplerian telescope. Eyepiece focal length, f_e; objective focal length, f_o.

The set up that you will be constructing in this experiment will be used for a number of other experiments (#4, 6, 7, and 10) that require expanded laser beam illumination. It is worthwhile to write down in your note book anything that helps you to rapidly set up and align the beam expander, since you will be doing this again.

Notes on Alignment of Laser Beams

Tape a card with a hole slightly larger than the laser beam to the output end of the laser, so that the beam will pass through and back reflections from components can be easily seen.

For each lens there are two reflections, one from each surface. When the centers of the two reflections are at the height of the laser beam, the height of the lens is properly adjusted. When they are overlapping, the beam is at the center of the lens. And when they are centered about the laser output, the lens is not tilted with respect to the beam.

In some cases, if the return beam is too strong (as in the case of this experiment), the laser will give an erratic output because vibrations from the outside world can be coupled into the laser. However, in the case of items such as beam expanders, where you do not try to send all the light back into the laser, the small reflections from the components have no measurable effect on the projects described in this manual.

Newport Equipment Required:

Part	Catalog #	Qty	Description
LA		1	Laser Assembly
BSA-I		2	Beam Steering Assy
LCA		2	Lens Chuck Assembly
TA-I		1	Target Assembly
LKIT-2		1	Lens kit, specifically
LP2	KPX106	1	200 mm focal len. lens
LP3	KPX076	1	25.4 mm focal len. lens
LN1	KPC043	1	-25 mm focal len. lens

Additional Equipment Required:

Part	Qty	Description
QI	1	Index card
	1	Tape
	1	Non-shiny, non-metallic ruler or meterstick

Table 3.1 - Required Equipment

Experimental Set Up:

1. Mount a laser assembly (LA) to the rear of the breadboard. Adjust the position of the laser such that the beam is parallel to the edge and on top of a line of tapped holes in the breadboard top. Tape an index card with a small (about 2 mm) hole in it to the front of the laser, so that the laser beam can pass through it. This card will be used as a screen to monitor the reflections from the components as they are inserted in the beam. These reflections, when they are centered about the beam output, indicate that lens is centered in the beam with its optic axis parallel to the beam.

2. Mount a beam steering assembly (BSA-I) approximately 4 inches in from the far corner of the breadboard (**Fig. 3-2**). Adjust the height of the mirror mount until the beam intersects the center of the mirror. Then rotate the post in the post holder until from the laser beam is parallel to the left edge and the surface of the optical breadboard.

3. Place a second beam steering assembly (BSA-I) in line with the laser beam at the lower left corner of the optical breadboard. (**Fig. 3-2**). Adjust the mirror mount until the laser beam is parallel to the front edge and the surface of the optical breadboard.

4. Use a meter stick or ruler to measure the beam at several distances from the output of the laser. The distances should be up to 10 m, if the room allows it. You will have to estimate the beam size, since, as was discussed in the Primer, the beam irradiance falls off smoothly from the center. Record the beam sizes at various distances about a meter apart. Calculate a divergence for the laser beam. Record the beam sizes at various distances about a meter apart. As indicated in the Primer, the beam diameter varies as

$$d^2(z)=d_0^2+\theta^2z^2. \qquad (0\text{-}25)$$

Assume that d_0 is the beam diameter measured close to the laser and that z is the distance from the laser, use the above equation to determine the value for θ based upon the measurement at various values of z. You will find the values of θ are more accurate for larger values of z. The average of measured values should be in the neighborhood of 1 milliradian.

The Galilean Beam Expander

5. Insert a short focal length (-25.4 mm) negative lens (LN1) into a lens chuck assembly (LCA) and mount it five inches from the first beam steering assembly. Align the lens by raising or lowering the post in the post holder and sliding the LCA so that the diverging beam is centered on the mirror of the second beam steering assembly. You can also use the alignment hints given previously.

6. Insert a longer positive focal length (200 mm) lens (LP2) into an LCA and place it about 175 mm (the sum of the focal lengths of the two lenses, remembering the first lens is a negative lens) from the first lens in the diverging laser beam.

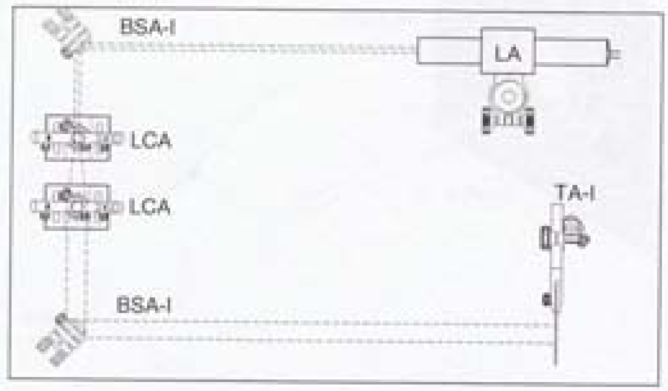


Figure 3-2. Schematic view of Galilean beam expander experiment.

Again, center the beam on the mirror of the second BSA and use the reflections off the lens to assist in aligning the beam.

7. Rotate the second BSA such that the beam returns back through the two lenses just to either side of the laser output aperture. (If the return beam enters the output aperture the laser may exhibit intensity fluctuations and you cannot determine the size of the return beam).

8. Carefully adjust the position of the last lens by moving it back and forth along the beam until the returning beam is the same size as the output beam.

9. Rotate the second BSA and shine the laser beam to the end of the room and measure the diameter just after the beam expander and at a number of places along the beam (at least a meter apart). Depending upon the accuracy of your alignment and distance available, it may be difficult to see any divergence at all.

10. As was discussed above, the divergence decreases with increasing beam waist diameter. The beam expander increases the diameter of the beam and as a result decreases the divergence of the beam in the same ratio as the beam expansion. Although it is difficult to be accurate in measuring the divergence, compare the estimate of the divergence of the undiverged beam divided by the power of the telescope. You may wish to try other combinations of lenses. Be sure that you do not choose a lens combination that, at the correct separation, has a beam which overfills the second lens and causes diffraction (See **Project #4**).

The Keplerian Beam Expander:

1. Replace the negative lens (LN1) with a short focal length positive lens (25.4 mm.) (LP3) and use the same adjustments to center the beams in the lenses and the mirror of the second BSA. Adjust the distance between the two lenses to be the sum of their focal lengths (**Fig. 3-2**).

2. Adjust the last beam steering mirror again for the condition of equal spot size at the laser output.

3. Repeat steps 7, 8, and 9 in the Galilean Beam Expander including an estimate of the collimation

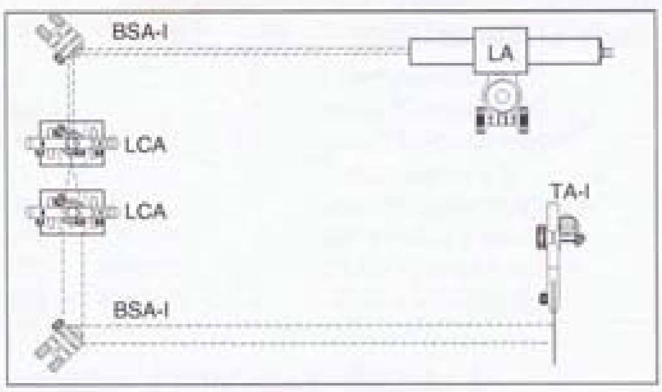


Figure 3-3. Schematic view of Keplerian beam expander experiment.

Note:

Either of these beam expanders can be used in Projects #4, 6, 7, and 10. The beam expander you construct depends more on the required expansion ratio than anything else.

of the laser beam for this geometry. You are encouraged to try other lens combinations.

Project #4

Diffraction of Circular Apertures:

Most of the optical systems that you will work with are made up of components whose apertures are circular. They can be mirrors, lenses, or holes in the structures that contain the components. While they do permit light to be transmitted, they also restrict the amount of light in an optical system and cause a basic limitation to the resolution of the optical system.

In this experiment you will measure the diffraction effects of circular apertures (**Fig. 4-1**). The diffraction associated with the size of the aperture determines the resolving power of all optical instruments from the electron microscope to the giant radiotelescope dishes. In addition, you will discover that a solid object not only casts a shadow but that it is possible for a bright spot to appear in the center of the shadow!

The diffraction patterns you will examine are located both close to the diffraction aperture and far away. The first is called **Fresnel** (Freh - NEL) diffraction; the second is **Fraunhofer** (FRAWN - hoffer) diffraction.

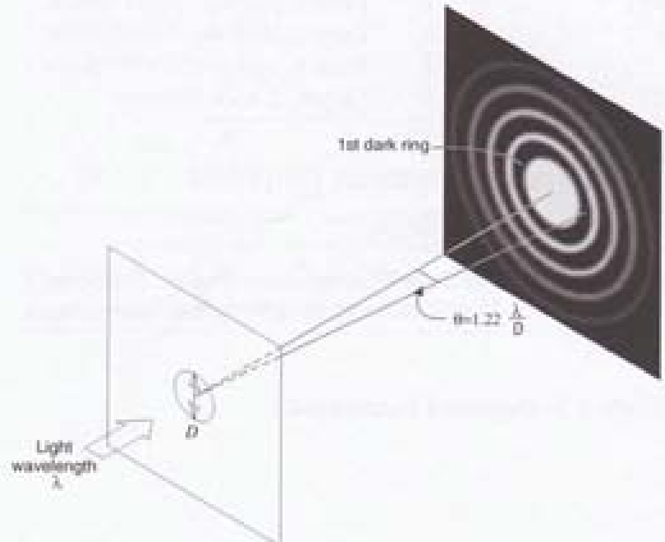


Figure 4-1. Diffraction from a circular aperture.

WARNING.

To be able to see some of the diffraction patterns, this experiment will be performed in a darkened room. Extreme care should be taken concerning the He-Ne laser beam. Your pupils will be expanded and will let in <u>60</u> times more light than in a lighted room. DO NOT LOOK AT A DIRECT SPECULAR REFLECTION OR THE DIRECT LASER BEAM. BE AWARE OF YOUR SURROUNDINGS AND FELLOW CO-WORKERS.

Newport Equipment Required:

Part	Catalog #	Qty	Description
LA		1	Laser Assembly
BSA-I		2	Beam Steering Assy
LCA		2	Lens Chuck Assy
TA-I		1	Target Assy
TA-II		1	Target Assy
LP4	KPX100	1	150mm focal length lens
LN1	KPC043	1	-25mm focal length lens
TP1		1	Target, pinhole, 0.001" diam.
TP2		1	Target, pinhole, 0.002" diam.
TP3		1	Target, pinhole, 0.080" diam
TF		1	Target, 3 zone Fresnel

Additional Equipment Required:

Part	Qty	Description
QI	1	Index card
QW	1	Metric ruler or meterstick

Table 4.1 - Required Equipment

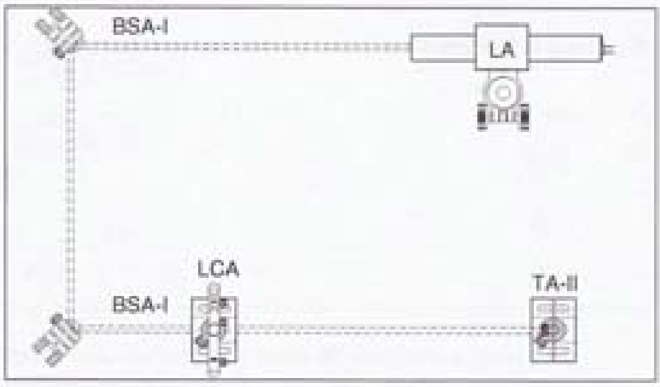


Figure 4-2. Schematic view of Fraunhofer diffraction experiment using TP1.

WALKING IN A DARKENED ROOM CAN BE HAZARDOUS!

Experimental Set Up:

1. Mount a laser assembly (LA) at the rear of the breadboard. Adjust the position of the laser such that the beam is parallel to the edge and on top of a line of tapped holes in the breadboard. Tape an index card with a small (about 2 mm) hole in it to the front of the laser, so that the laser beam can pass through it. This card will be used as a screen to monitor the reflections from the components as they are inserted in the beam. See the note in **Project #3** on the alignment of laser beams.

2. Mount a beam steering assembly (BSA-I) approximately 4 inches in from the far corner of the breadboard (**Fig. 4-2**). Adjust the height of the mirror mount until the beam intersects the center of the mirror. Then rotate the post in the post holder until the laser beam is parallel to the left edge and the surface of the optical breadboard.

3. Place a second beam steering assembly (BSA-I) in line with the laser beam at the lower left corner of the optical breadboard, (**Fig. 4-2**). Rotate and adjust the mirror mount until the laser beam is parallel to the front edge and the surface of the optical breadboard.

4. Place an index card in a modified target holder assembly (TA-II) and set it at the end of the breadboard so that the beam hits the center of the card.

5. Mount a lens chuck assembly (LCA) five inches to the right of the last beam steering mirror and directly in line with the laser beam. This will be the aperture holder.

Fraunhofer Diffraction of a Circular Mask

6. Carefully place the pinhole target (TP1) into the LCA. Adjust the mount such that the laser beam strikes the target approximately in the center. **WARNING — The target will reflect a large percentage of the beam.**

7. Adjust the last beam steering mirror such that the laser beam fills the pinhole. This can best be accomplished by viewing the back side of the target (beyond the laser) from 45° and looking for a bright red glow. This will occur when the laser beam (or part of the laser beam) is illuminating the aperture.

8. Watch the white card. Carefully adjust the last beam steering mirror to produce the brightest image. You should see a bright central circle surrounded by dark and light circular bands. This is the Airy disc pattern. Measure the distance from TP1 to the index card in TA-II. Mark and then measure the diameter of the first dark circular band around the bright central circle. This is a measure of the amount of diffraction caused by the pinhole.

9. As was pointed out in the Primer, the angular subtense of the dark band is related to the wavelength and diameter of the pinhole by

$$\sin\theta = 1.22\,\lambda / D \qquad (0\text{-}11)$$

where D is the diameter and λ is the wavelength. Since the diffraction angle is small, the sine and the tangent of the angle are equal. The tangent is found from dividing the **radius** of the dark band by the distance from the pinhole to the index card that was recorded in step #8. Inserting the wavelength of the He-Ne laser (λ = 633 nm) into the equation, calculate the diameter of the pinhole.

10. All circular apertures will exhibit an Airy pattern. Replace the TP1 with TP2. You will need to use a target holder mount (TA-I) approximately four inches in from the breadboard edge and in line with the position of the lens chuck assembly. Measure the diameter of the first dark band and the distance between the pinhole and the index card. Calculate the pinhole diameter based on this data.

This series of rings from a circular aperture causes objects that are close together to overlap at the focal plane of the observing instrument and will limit the resolving power of large aperture telescopes.

11. Assemble a 6:1 beam expander, using the techniques of **Project #3**, between the first and second beam steering mounts (BSA-I) as shown in **Fig. #4-3**. Replace TP2 with TP3. Because the **aperature** is so large, replace the card mount TA-II with a third BSA-I and direct the beam to a wall more than 10 feet away. Measure the diameter of the first dark band and estimate the distance between the pinhole and the wall. Calculate the pinhole diameter.

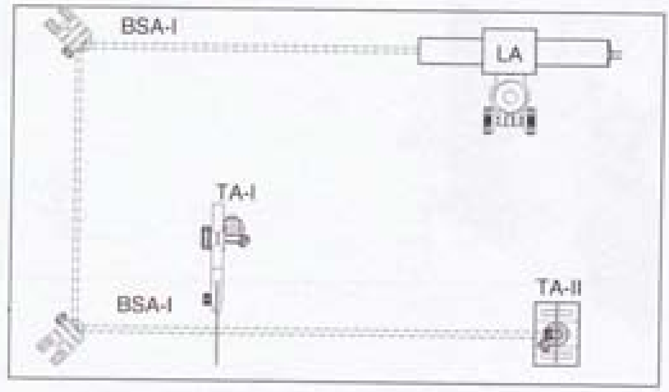


Figure 4-2. Schematic view of Fraunhofer diffraction experiment using TP2.

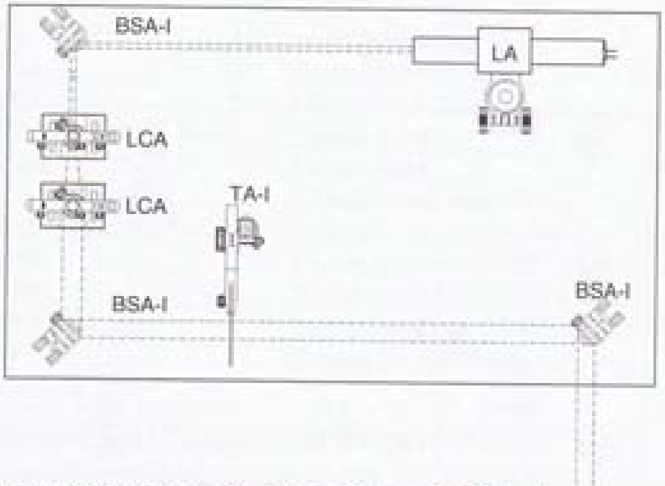


Figure 4-3. Schematic view of Fresnel diffraction experiment.

In the Primer we discussed that at far field the Fraunhofer diffraction pattern does not change in shape, but only in size. Using the index card, look at the diffraction pattern starting at the pinhole and moving away toward the wall. At a distance of about 2 feet from the pinhole you will see the center bright spot become a small dark spot. Depending on how well the beam expander is set, this small dark spot may be difficult to resolve. However, the center spot changing from bright to dark and then to bright again is Fresnel diffraction.

Fresnel Diffraction of Circular Mask

12. Replace TP3 with the Fresnel target (TF). Look at the diffraction pattern on the target screen. Note that the center of the image has several bright and dark rings. This is also Fresnel diffraction. Depending on the distance of TA-II from TF, the center of the pattern may be bright or dark. Although the Fresnel target (TF) has a central absorbing circle, note there is still light at the center of the pattern. The bright spot at the center is sometimes called the Poisson spot or the spot of Arago.

13. Examine the shadows of other objects put in the expanded laser beam. Pencil points, wires, and small beads on a string are good objects that give interesting Fresnel patterns. Note how the patterns change as you move the objects along the beam direction. Sketch some of the more interesting patterns in your notebook.

A detailed description of the results can be found in **The Optics Problem Solver** by The Research and Education Association.

Project #5

Single Slit Diffraction and Double Slit Interference:

Diffraction of light occurs whenever light illuminates an aperture that has dimensions that are on the order of the wavelength of light being used. In the case of a slit which has a narrow opening that is "infinitely" tall, the diffraction takes place in the direction perpendicular to the small dimension.

In addition light from one slit will interfere with the light from a second nearby slit to produce an interference pattern that combines the interference properties of the single slit with the interference pattern of two nearby sources. **(Fig. 5-1)**

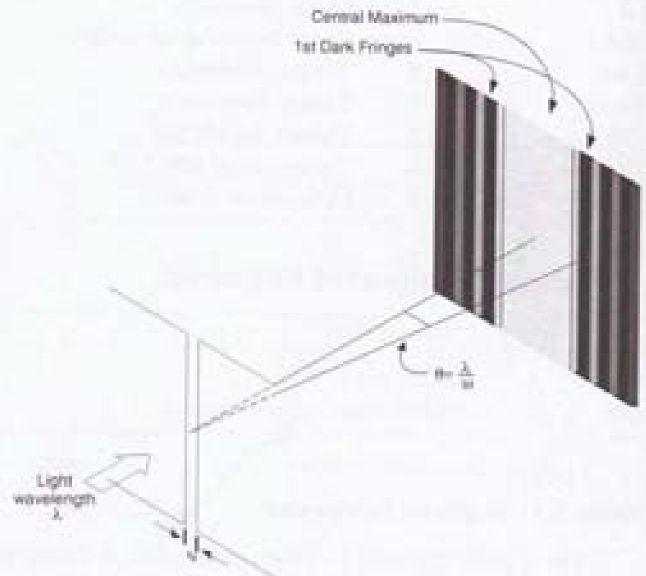


Figure 5-1. Diffraction from a single slit.

Experimental Set Up:

1. Mount a laser assembly (LA) to the rear of the breadboard (**Fig 5-2**). Adjust the position of the laser such that the beam is parallel to the edge and on top of a line of tapped holes in the breadboard top. Tape an index card with a small (about 2 mm) hole in it to the front of the laser, so that the laser beam can pass through it. This card will be used as a screen to monitor the reflections from the components as they are inserted in the beam. See the note in **Project #3** on the alignment of laser beams.
2. Mount a beam steering assembly (BSA-I) approximately 4 inches in from the far corner of the breadboard (**Fig. 5-2**). Adjust the height of the mirror mount until the beam intersects the center of the mirror. Then rotate the post in the post holder until the laser beam is parallel to the left edge and the surface of the optical breadboard.
3. Place a second beam steering assembly (BSA-I) in line with the laser beam at the lower left corner of the optical breadboard, (**Fig. 5-2**). Rotate and adjust the mirror mount until the laser beam is parallel to the front edge and the surface of the optical breadboard.
4. Place an index card in a modified target holder assembly (TA-II) and mount it at the end of the breadboard so that the beam hits the center of the card.

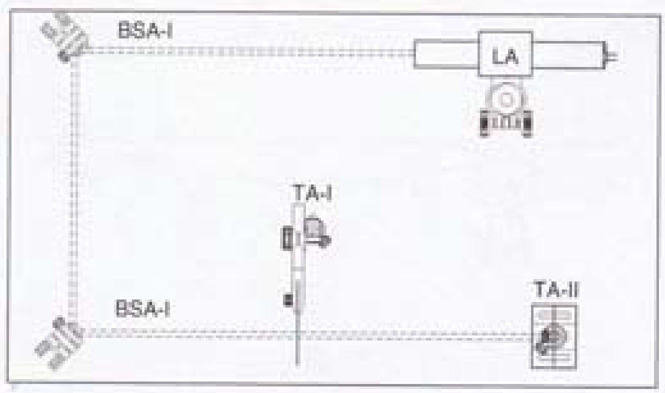


Figure 5-2. Schematic view of diffraction experiments.

Newport Equipment Required:

Part	Cat #	Qty	Description
LA		1	Laser Assembly
BSA-1		2	Beam Steering Assembly
TA-1		1	Target Assembly
TA-11		1	Target Assembly
TSS		1	Target, single slit
TDS		1	Target, dual slit
DG		1	Diffraction grating

Additional Equipment Required:

Part	Qty	Description
QI	1	Index card
QW	1	Metric ruler or meterstick

Table 5.1 - Required Equipment

5. Mount a TA-I five inches to the right of the last beam steering mirror and four inches in from the laser beam. This will be the holder for parts TSS and TDS.

Single Slit Diffraction

6. Carefully place the TSS (single slit – 0.002 in. wide) into the TA-I. Adjust the mount such that the laser beam strikes the target approximately in the center.

WARNING

The target will reflect a large percentage of the beam.

7. Adjust the last beam steering mirror such that the laser beam fills the slit. This can best be accomplished by viewing the back side of the target from 45° and looking for a bright red glow. This will occur when the laser beam is illuminating the slit.

8. Watch the white card. Carefully adjust the last beam steering mirror to produce the brightest image. You should see a bright central band with several dimmer bands on each side. This is the single slit diffraction pattern. Mark on the index card the locations of as many dark bands as you can easily see. Note that the central band is larger than the sidebands. Measure the distance between the center of the dark bands on both sides of the central band and the distance from the slit to the index card. Calculate the angle at the slit between the central peak and the first dark band. Remember the distance between the first dark bands is twice the distance between the central part and the first dark band. Based on expressions given in the Primer, the angular subtense of the center band from central peak to first dark band is given by

$$\sin\theta = m\lambda/\omega \qquad (0\text{-}9)$$

If the wavelength of the He-Ne laser is 633 nm, determine the width of the slit from your calculations.

Young's Double Slit Experiment

1. A second and related experiment can be performed with the previous setup. Replace the TSS with a TDS (dual slit – 0.002 in. wide with 0.008 in spacing) target and the index card used as the observation screen. Measure the slit to index card distance *R*.
2. The pattern will now have a series of maxima and minima spaced within the envelope of the original single slit pattern. These fringes are the interference pattern of the double slit. Mark the locations of the minima $x_1, x_2 \ldots$ of these closely spaced fringes. Calculate the average separations $\Delta x = x_1 - x_2$. Also mark the location of the minimum of the large band (the position where the interference fringes disappear).
3. Calculate the fringe separation from

$$\Delta\theta = \Delta x / R \tag{5-2}$$

and record it in your notebook. From this value of $\Delta\theta$ and the wavelength of the laser (λ=633nm) you can calculate the slit separation using **Eq. 0–16** in the primer.

4. Take a card or the edge of a ruler and carefully insert it in front of one of the two slits. This takes a little practice. If you do it right you will see the interference pattern disappear and a single slit diffraction pattern remain. Note that when you take away the item blocking the light from any of the slits, you introduce dark fringes. Of course the light at the bright fringes is brighter. You are using light to push light around!

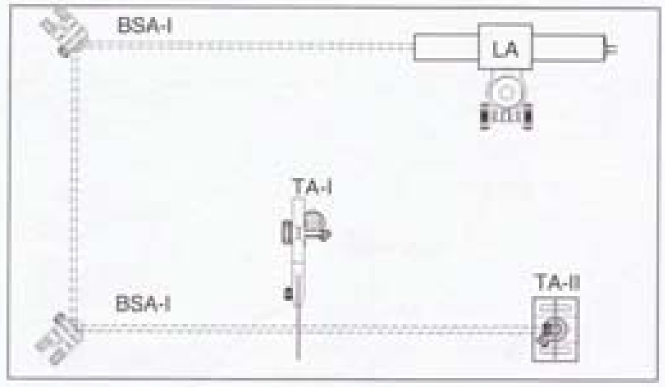


Figure 5-3. Schematic view of Young's double slit experiment.

Additional experiments:

Diffraction grating

Higher order diffraction patterns exist for 3,4,5 ... equally spaced slits. Eventually, the number of slits becomes very large and the results approaches the diffraction grating described in **Section 0.4.3** in the Primer. Most high resolution instruments for determining the transmission or reflection characteristics of optical materials and coatings use some form of a grating.

1. Mount a diffraction grating (DG) in the TA-1 and illuminate it with the laser beam. Mount a new index card in the TA-II and locate it behind DG, so that a number of diffraction orders can be seen.

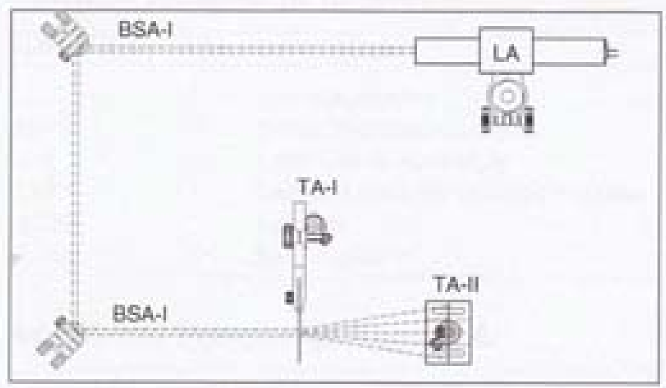


Figure 5-4. Schematic view of diffraction grating experiment.

2. Move the TA-II away from DG until only a few dots remain on the screen and their separations are easily measured. Mark the locations of the diffraction orders on the card and label each with the order (0 for the undiffracted beam). Measure the distance from DG to the screen.

3. Calculate the diffraction angles from the measurements. Note the angles are large enough that you cannot use any small angle approximation. You must use the inverse tangent to arrive at the angle.

4. The groove separation, or grating constant, for this grating is found by taking the reciprocal of the grating frequency, which is 13,400 grooves per inch. From the groove separation and the angular measurements for several orders, determine the wavelength of the helium-neon laser. Compare it to 633 nm.

The spectra of other sources can be studied using this diffraction grating, but additional components are required. Since most will not be lasers with sharply defined beams, the sources illuminate a slit. The light from the slit is then collimated to provide a constant angle of incidence to the grating. The diffracted beams are then refocused to a series of slit images that are separated into the colors in the spectrum of the source located in the focal plane of the focus lens. See any of the major optics references for description of a simple transmission grating spectrometer.

In most commercial spectrometers, the diffraction grating is a reflection, rather than a transmission type. This is because the instrument is more compact and the gratings tend to be more efficient in this mode.

Project #6

The Michelson Interferometer:

In this experiment you will build a Michelson interferometer similar to the one described in the Primer and use it as a means to observe small displacements and refractive index changes. When this arrangement of components is used to test optical components in monochromatic light it is called a Twyman-Green interferometer. The Twyman-Green interferometer is widely used for testing optics and optical systems, and provides a means for measuring the amount of aberrations present in these optical systems. Rather than make such a distinction here, the device will be referred to as a Michelson interferometer throughout this manual.

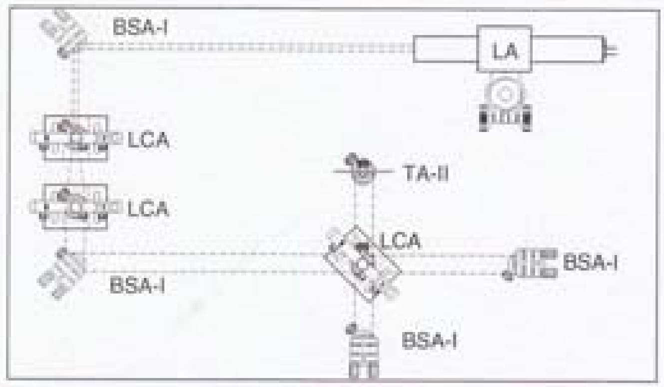


Figure 6-1. Schematic view of Michelson Interferometer experiment.

Experimental Set Up:

1. Mount a laser assembly (LA) to the rear of the breadboard (**Fig 6-1**). Adjust the position of the laser such that the beam is parallel to the edge and on top of a line of tapped holes in the breadboard top. Tape an index card with a small (about 2 mm) hole in it to the front of the laser, so that the laser beam can pass through it. This card will be used as a screen to monitor the reflections from the components as they are inserted in the beam. See the note in **Project #3** on the alignment of laser beams.
2. Mount a beam steering assembly (BSA-I) approximately 4 inches in from the far corner of the breadboard (**Fig. 6-1**). Adjust the height of the mirror mount until the beam intersects the center of the mirror. Then rotate the post in the post holder until the laser beam is parallel to the left edge and the surface of the breadboard.
3. Place a second beam steering assembly (BSA-I) in line with the laser beam at the lower left corner of the breadboard, (**Fig. 6-1**).
4. Set up a beam expander between the first two BSA-I's as explained in **Project #3**. This beam expander generates an expanded plane wave that is needed to build the interferometer.

Newport Equipment Required:

Part	Cat #	Qty	Description
LA		1	Laser Assembly
BSA-I		4	Beam Steering Assembly
LCA		3	Lens Chuck Assembly
TA-II*		1	Target Assembly without B-2 base
LKIT-2		1	Lens kit
FK-BS		1	Beam splitter

Additional Equipment Required:

Part	Qty	Description
QI	1	Index card
QS	1	Soldering iron

Table 6.1 - Required Equipment

5. Place a lens chuck assembly (LCA) approximately five inches to the right of the last BSA-I mount. Mount a 50/50 beam splitter in the LCA and rotate the assembly 45 degrees to the optical path. The beam reflected off of the first surface should be perpendicular to and going in the direction of the front edge of the breadboard. The beamsplitter divides the incoming laser beam into two equal components for the two arms of the interferometer.

6. Place a BSA-I with its mirror centered about the path of the reflected beam and about five inches from the beamsplitter such that the beam is retro-reflected back onto the index card taped to the laser. This mirror will be called the reference mirror.

7. Place a second BSA-I with its mirror centered about the path of the transmitted beam five inches beyond the beam splitter to intercept the transmitted beam (**Fig. 6-1**). Adjust the mirror until its beam is directed back to the index card taped to the laser. This mirror will be called the test mirror.

8. Use a TA-II* (no base) with an index card (QI) as an observation screen on the other side of the beamsplitter from the reference mirror (See Step 6). Adjust the mirrors in the two arms of the interferometer until the two beams overlap on the screen. There should be combined reflections at the observation screen and on the card at the front of the laser. Aligning the two beams on the card at the front of the laser is good for a quick rough alignment.

9. As the two beams are brought into coincidence, a series of bright and dark fringes should appear representing the interference pattern between the two wavefronts. The orientation and separation of the fringes can be controlled by adjusting the reference and test mirrors. Usually it is best to use one mirror for adjustment. Adjust the mirror so that approximately five fringes appear across the beam on the card. The number of fringes can be varied in a particular direction by tilting the reference mirror in a direction perpendicular to the direction of the fringes. Your Michelson interferometer is now completed.

10. Any curvature present in the fringes represent phase differences between the waves that have traversed the two arms of the interferometer, i.e. the reference mirror arm and the test mirror arm. If the reference mirror is assumed to be perfectly

flat, then the curvature in the fringes may be due to the fact that the mirror under test is not flat, but has a long radius of curvature or aberrations. These aberrations cause the plane wave, generated by the beam expander, in the test arm to depart from a plane wave. The interference of the plane wave reference wavefront with the test mirror wavefront will create a pattern of curved fringes with varying separation. The amount of the departure of a curved fringe from a straight line, represents the phase shift introduced by the component under test. This departure, measured in number of fringes, gives twice the departure of the test wavefront from the reference wavefront in wavelength of laser light. The amount of test mirror aberration (W) may be calculated as follows:

$$W = (\text{fringe shift})/2 \qquad (6\text{-}1)$$

where W is expressed in units of the wavelength of the laser used (in this case the laser wavelength is 633 nm), and fringe shift is the height of the fringe expressed in units of the average fringe separation distance in the interference pattern. The factor of two arises from the fact that reflection doubles the amount of aberration.

11. Move the second lens of the beam expander slowly toward the first. The expanded beam now diverges, causing the wavefront to be spherical instead of planar. The fringes will become circular and if you further adjust the beam coincidence, a bull's-eye pattern can be seen.

12. Turn the soldering iron (QS) on, and after it warms up place it in the path of the light in the test arm. Observe the changes in the fringes around the tip of the soldering iron. The shift in the fringes is due to the extra phase shift introduced by the hot air surrounding the iron tip. Hot air has a different density and refractive index than cold air and consequently the two arms have a different optical path-lengths.

13. Insert your finger partway into one of the arms of the interferometer, so that its shadow can be seen on the screen. Notice the variations in the fringes just due to the heat of your finger. Also hold your hand palm up just below one of the interferometer arms.

14. Push on the test mirror and note that very little force leads to tiny deflections of the test mirror. These deflections are measurable as indicated by the shift in the fringes. For each fringe that

moves past a point in the center of the pattern the mirror has moved one half wavelength along the beam direction. Try to devise a means of slowly moving one mirror. If the motion is slow enough you can count the number of fringes and determine the amount of mirror displacement.

15. Another means of changing the optical path inside the interferometer is to insert a transparent material, such as a microscope slide or other flat material, in one of the arms. The departure of the fringe pattern from the undisturbed system is a measure of the refractive index and thickness variation in the material.

Additional experiments:

Distance measurement.

Time dependence of the fringes

1. After setting up the Michelson interferometer, monitor the change in the fringe pattern as a function of time. Usually thermal changes will cause small expansion and contractions in the component distances and this will result in a shift of the fringes with time.

Vibration dependence of the fringes

2. Tap on the surface of the table and monitor the changes in the fringes. How long does it take the vibration to damp out? Do you detect any vibrational motion when you slam a door, walk across the room, or jump up and down? Some tables have air cushions or springs to isolate an optical system such as a Michelson Interferometer from the vibrations of the outside world.

Motion detector

3. This is a somewhat more elaborate experiment and requires a light detector such as a photocell or phototransistor. *Replace the observation screen with the detector and a large pinhole that allows only one fringe to pass. When the fringe pattern moves the light on detector will create alternately strong and weak signals. If the detector is hooked up to an audio amplifier and speaker, the alternating signal will provide an audible sound. The frequency of the sound will depend upon the number of fringes per second that sweep past the pinhole. Since each fringe represents one half wavelength mirror movement, the pitch of the sound wave represents the speed of motion of the mirror.

The circuit for a simple photocell detector is given at the end of ***Project #8.***

Project #7

Coherence and Lasers:

This project is a departure from the classical optics experiments described up to this point in this manual. In this project you will examine one of the characteristics of lasers with a Michelson interferometer to determine the frequency separation between the axial modes of a laser (**Section 0.6.3**). The standard He-Ne laser supplied in the kit produces three wavelengths separated in frequency by $c/2L$, where c is the speed of light and L is the distance between the ends of the laser mirrors (approximately the length of the laser tube).

The technique used for this project was described in **Section 0.6.4** in the Primer. By observing the visibility of the fringes of the Michelson interferometer you will be able to measure the frequency between axial modes in the laser. The Michelson interferometer is described in **Section 0.4.2** in the Primer and was constructed in **Project #6**.

Experimental Set Up

NOTE:

If you have already built a Michelson interferometer in Project #6, the set up is almost complete. The only modification you will have to make is to change the reference mirror (Step 5) from a fixed base assembly that screws into the optical table to a movable assembly by attaching a B-2 base from one of the LCA assemblies to the BSA-I assembly (Fig 7-1). Also, adjust the beam expander for a planar wavefront; the small reflected beams on the card at the front of the laser will make coincident alignment much quicker. Once this is done you can start at Step #10. Because the reference mirror assembly is no longer fixed, you will have to readjust to find the fringes every time you move or bump this assembly. Patience!

1. Mount a laser assembly (LA) to the far side of the breadboard (**Fig 7.1**). Adjust the position of the laser such that the beam is parallel to the edge and in line with a line of tapped holes in the breadboard top. Tape an index card (QI) with a small (about 2 mm) hole in it to the front of the laser, so that the laser beam can pass through it.

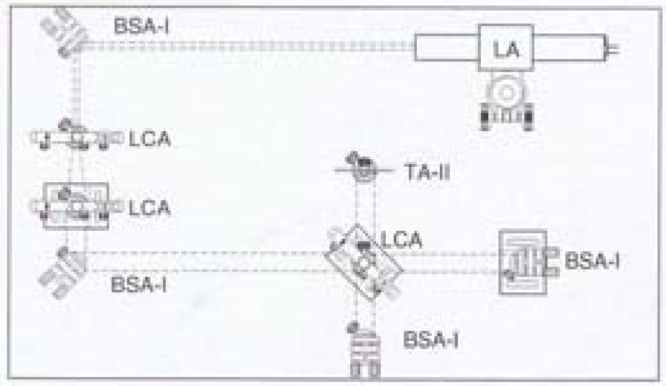


Figure 7-1. Schematic view of coherence experiment.

Newport Equipment Required:

Part	Qty	Description
LA	1	Laser Assembly
BSA-I	3	Beam Steering Assembly
BSA-I*	1	Beam Steering Assembly with B-2 Base
LCA	3	Lens Chuck Assembly
TA-II*	1	Target Assembly without B-2 base
LKIT-2	1	Lens Kit
FK-BS	1	Beam Splitter

Additional Equipment Required:

Part	Qty	Description
QI	1	Index Card
QW	1	Measuring Tape

Table 7.1 - Equipment Required

This card will be used as a screen to monitor the reflections from the components as they are inserted in the beam. See the note in **Project #3** on the alignment of laser beams.

2. Mount a beam steering assembly (BSA-I) approximately 4 inches in from the far corner of the breadboard (**Fig. 7-1**). Adjust the height of the mirror mount until the beam intersects the center of the mirror. Then rotate the post in the post holder until from the laser beam is parallel to the left edge and the surface of the optical breadboard.

3. Place a second beam steering assembly (BSA-I) in line with the laser beam at the lower left corner of the optical breadboard (**Fig. 7-1**).

4. Set up a beam expander between the first two BSA-I's as explained in **Experiment #3**. Mount the first lens to the optical table without a B-2 base (**Fig 7-1**). This beam expander generates an expanded plane wave that is needed to build the interferometer.

5. Place a lens chuck assembly (LCA) approximately five inches to the right of the last BSA-I mount. Mount a 50/50 beam splitter in the LCA and rotate the assembly 45 degrees to the optical path. The beam reflected off of the first surface should be perpendicular to and going in the direction of the front edge of the breadboard. The beamsplitter divides the incoming laser beam into two equal components for the two arms of the interferometer.

6. Place a BSA-I with its mirror centered about the path of the reflected beam five inches from the beam splitter to intercept the reflected beam (**Fig. 7-1**). Adjust the mirror until its beam is directed back to the index card taped to the laser. This mirror will be called the fixed mirror.

7. Place a BSA-I* (modified with a B-2 base, so that it may be moved on the optical table) with its mirror centered about the path of the transmitted beam and about five inches beyond the beam splitter such that the beam is retro-reflected back to the laser. This mirror will be called the moveable mirror.

8. Use a TA-II* (no base) with an index card (QI) as an observation screen on the other side of the beamsplitter from the fixed mirror (see Step 6). Adjust the mirrors in the two arms of the interfer-

ometer until the two beams overlap on the screen. There should be combined reflections at the observation screen and on the card at the front of the laser.

9. As the two beams are brought into coincidence, a series of bright and dark fringes should appear representing the interference pattern between the two wavefronts. The orientation and separation of the fringes can be controlled by adjusting the moveable and fixed mirrors. Usually it is best to use one mirror for the adjustment mirror. Adjust the mirror so that approximately five fringes appear across the beam on the card. The number of fringes can be varied in a particular direction by tilting the reference mirror in a direction perpendicular to the direction of the fringes. Your Michelson interferometer is now adjusted.

10. Adjust the mirror position until the path difference between the two arms of the Michelson interferometer are equal. In this case, however, the two paths are not quite equal since the light that has to pass through the glass to reflect off the beamsplitter travels an additional distance, since the path inside the glass must be multiplied by the refractive index of the glass. In the case of the beamsplitter (FK-BS), the additional optical path length amounts to approximately $2\sqrt{2}$ times the thickness of the beamsplitter.

11. Place the measuring tape on the breadboard with some major division on it even with the center of the beamsplitter. Record the value in you notebook.

12. Translate the moveable mirror away from the beamsplitter by ½ inch increments. Each time the mirror is moved readjust the mirror tilt until four to six fringes are observed. There will be a position in path difference where the fringes seem to fade in and out. Carefully move the mirror about this position until the fringes cannot be made to appear. Record this position.

13. Continue to move the mirror away from the beamsplitter and observe that the contrast increases. Using the same technique as above, look for the mirror positions that give the strongest possible contrast. You may have to go beyond that position and return several times in order to verify your judgement. Record the value for the contrast maximum.

14. Attempt to find additional contrast maxima and minima. If you are able to do so, record these positions also. The distance between successive maxima and minima should be the same. If you do have more than one value, take the average of the maximum to minimum distances.

15. From the Primer (**Section 0.6.4**) it was shown that if the fringe visibility went from a maximum to a minimum in a distance ΔL, the frequency separation between two outputs of a laser that caused this contrast variation is

$$\Delta\upsilon = c/2L = \lambda\upsilon/4\Delta L = c/4\Delta L . \qquad (7\text{-}1)$$

Calculate the frequency difference based on the values you have measured for ΔL.

16. It was shown that the frequency separation between the neighboring modes of a laser was $c/2L$. Based on the frequency separation just determined in Step #15, find the distance between mirrors in the laser tube you are using. Is this value reasonable based on the exterior dimensions of the laser?

Additional experiments:

If a polarizer is added to the system at the output of the laser while the mirror is at the location of minimum contrast and the polarizer is rotated parallel to the double mode output, the contrast of the fringes will be maximized. The modes contributing to the major contrast variation will now be separated by c/L. Since the modes are spaced twice as far apart as in the previous experiment, the contrast minimum will occur at one half the value of ΔL found in Step #15. Rotate the polarizer by 90° and observe the contrast variation as you move the mirror. Don't expect anything as dramatic as the effects you have just been measuring, since you are now observing the interference of a single mode laser. You would need the length of a football field difference in one of the arms in order to reduce the contrast. Thus the coherence length of this laser with a single mode selected by polarization is of the order of hundreds of meters. This can be compared to the coherence length of a standard laboratory grade sodium light source (0.045 nm half width @ λ = 550 nm) which has a coherence length of about 2 mm.

Project #8
Polarization of Light:

While the idea of polarization is fairly simple (**Section 0.5** in the Primer), it remains somewhat abstract until you can work with light and its various forms of polarization. The object of this project is to give you some experience in the orientation and generation of polarized light.

As was pointed out in the Primer (**Section 0.6.3**) and explored in **Project #7**, the output of the laser used in the Project in Optics Kit has three modes with two of the modes polarized orthogonally to the third mode. Because the laser has no special stabilization circuitry, the modes of the laser will tend to drift in frequency, so that one of the modes of one polarization may drop out and a mode of the orthogonal polarization pop in. So what had been the single mode polarization becomes the two mode polarization and vice versa! This phenomenon is referred to as **mode sweeping**. Its effect on these experiments is that the output of the laser in a particular polarization will change slowly over time.

So, as you take measurements during this experiment, be aware that some of the power variation may not be due to your efforts to change a variable, but may caused by mode sweeping effects. Two ways to minimize these effects are; (1) to let the laser warm up by turning it on as soon as you enter the lab and (2) take the data series more than once to account for any source variation. If there is time, you may want to monitor and record the power output of the laser for some period of time when you are not performing the experiments. These "baseline" measurements are useful to assess this power variation phenomenon.

NOTE: Part of this experiment requires a measurement of optical power levels. It is not possible for you to rely on your eye to perform this task. Its very construction with a diaphragm that closes down when the light gets too bright makes it a great image detector but a poor power meter. Therefore, some sort of optical detector must be used or constructed. If you do not have a Newport 615 or equivalent Optical Detector, you will need to obtain a standard laboratory voltmeter and construct a fairly simple detector. While there are a number of devices that will do the job, the instructions at the end of this Project should be sufficient to construct a simple photodetector circuit.

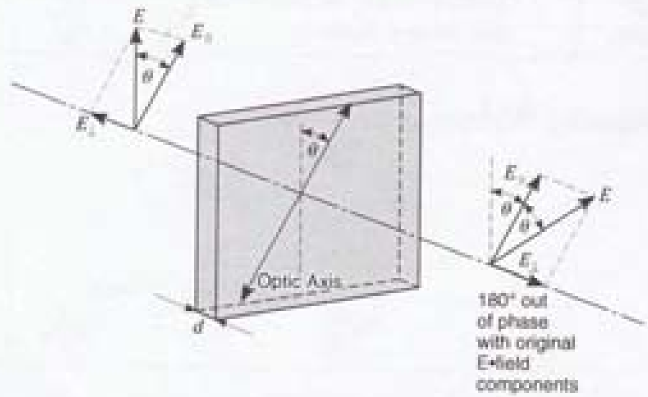


Figure 8-1. Half-wave plate. The plate produces a 180° phase lag between the $E_{\parallel}$ and $E_{\perp}$ components of incident linearly polarized light. If the original polarization direction is at an angle θ to the optic axis, the transmitted polarization is rotated through 2θ from the original.

Newport Equipment Required:

Part	Qty	Description
LA	1	Laser Assy
BSA-I	2	Beam Steering Assy
RSP-I	1	Rotation Stage Assy
LCA	2	Lens Chuck Assembly
TA-II	1	Modified Target Assy
R (RSP-1T)	1	Rotation Stage and Plug
	2	Linear Polarizer

Additional Equipment Required:

Part	Qty	Description
QI	1	Index Card
QV	1	Voltmeter
QD	1	Photodetector or Solar Cell
QM	1	Microscope Slide

Table 8.1 - Equipment Required

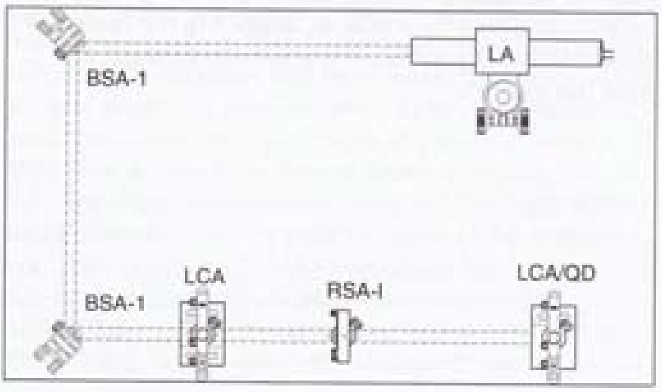


Figure 8-2 Schematic view of polarization of light experiment.

Experimental Set Up:

1. Mount a laser assembly (LA) to the rear of the breadboard. Adjust the position of the laser such that the beam is parallel to the edge and on to of a line of tapped holes in the breadboard top. Tape an index card with a small (about 2 mm) hole in it to the front of the laser, so that the laser beam can pass through it. This card will be used as a screen to monitor the reflections from the components as they are inserted in the beam. See the note in **Project #3** on the alignment of laser beams.

2. Mount a beam steering assembly (BSA-I) approximately 4 inches in from the far corner of the breadboard (**Fig. 8-2**). Adjust the height of the mirror mount until the beam intersects the center of the mirror. Then rotate the post in the post holder until the laser beam is parallel to the left edge and the surface of the optical breadboard.

3. Place a second beam steering assembly (BSA-I) in line with the laser beam at the lower left corner of the optical breadboard, (**Fig. 8-2**). Rotate and adjust the mirror mount until the laser beam is parallel to the front edge and the surface of the optical breadboard.

4. Place the detector in a lens chuck assembly (LCA) and mount it well beyond the second BSA-I so that the beam hits the center of the detector.

5. Mount a polarizer in an LCA assembly with the notch in the disk facing up. Tape a second polarizer by the edges to a rotation stage assembly (RSA-I) such that the notch is vertical when the rotation stage is set at 360°. Place both of these assemblies directly in line with the laser beam between the second BSA-I and the detector. The output of the device will be proportional to the irradiance of the light (Watts/m^2). This quantity is proportional to the square of the amplitude of the electric field, as discussed in Section 0.5.1 of the Primer. Rotate the second polarizer by 10° increments between 0° and 180°, recording the angle and the output of the detector as measured by the voltmeter.

6. Plot the results of your measurements and compare them to the **Law of Malus.**

$$I_{trans} = I_0 \cos^2\theta \qquad (0\text{-}18)$$

You will have to scale your comparison plot to the I_0, which is the maximum value recorded.

Also, you may have missed the orientation of one of the polarizers by some amount and therefore the two curves may be shifted along the angle axis. You may have to adjust your plots to make the comparison, but you should justify any adjustment in your notebook.

7. Remove the RSA-I from the bench and demount the Rotation Stage. Remove the polarizer and insert a plug in the 1 inch hole. Mount a Lens Chuck Assembly (LCA) without a base onto this stage by using the hole in the center of the plug. The Rotation Stage (R) is then attached to the table with 1/4-20 screws. Place the LCA such that the laser beam passes through the center of the lens holder. Tape a microscope slide (QM) to the lens holder so that the slide is held firmly in place and the beam does not pass through the tape (**Fig. 8-3**).

8. Set the Rotation Stage to 0°. Rotate the lens chuck in its holder so that the beam reflected from the slide is sent back along the input beam. You may want to use the index card with the hole in it to set the beam. Tighten the screw on the post, so that the lens chuck is fixed in the holder.

9. Rotate the polarizer so that the transmission direction is horizontal to the table (notch upward). This means that the polarization vector is now horizontal and in a plane formed by the laser beam direction and the normal to the surface of the microscope slide. The plane defined by these two directions is called the **plane of incidence.**

10. Replace the detector in the LCA with a modified target assembly (TA-II) since you are going to have to follow the beam on the table.

11. Rotate the Rotation Stage (R) away from 0° and observe the reflection from the slide on the index card mounted in TA-II. At some point in this process the reflection from the slide will become very dim. Scan past the point of minimum reflection and observe that the reflected beam irradiance increases. By successive approximations, bring the stage to produce the minimum reflection. (You may find that you can improve the minimum by slightly tweaking the input polarization angle by a small amount.) Record the angle of the Rotation Stage and determine the angle between the beam and the normal to the surface. Compare this angle to that of **Brewster's angle**, discussed in **Section 0.5.1** in the Primer, and the value given there.

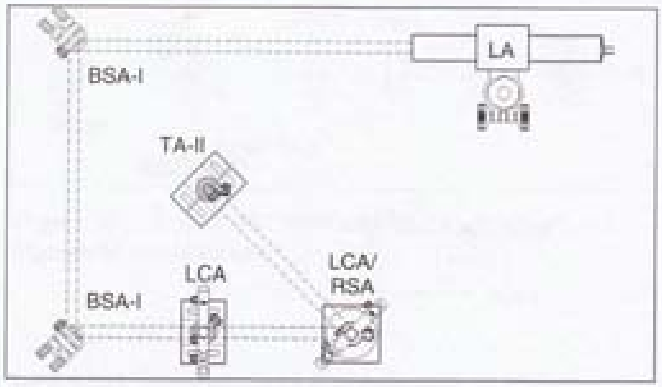


Figure 8-3. Schematic view of Brewster angle experiment.

12. Rotate the input polarization of the beam to the orthogonal polarization and observe that no such reduction in the reflected beam irradiance occurs at any angle.

Additional Exercises:

If your photodetector is sensitive enough, it is possible to measure the reflected power of the beam for both polarizations. A plot of the recorded powers as a function of the angle of incidence can be compared to the theoretical curves in most college optics texts in the sections of polarization of light by reflection.

Another use of polarized light is to measure the sugar content of various syrups in the candy making industry. The basis for this measurement is the fact that sugars are optically active materials, causing the plane of polarization of light passing through the liquid to rotate. The amount of rotation is dependent on the sugar concentration and the thickness of the sample through which the light travels. Thus by constructing a device with a standard sample length and knowing the rotation constant of the sugar, the concentration of an unknown sugared liquid can be determined.

For example, colorless corn syrup (Karo is standard brand) has a rotation constant for visible light that is easily measured. Using a clear plastic tank such as the one in **Project #1**, fill the bottom of the tank with syrup to height sufficient to pass a beam through and place it on a box or other object to raise the liquid to the correct beam height. Without the tank in the beam, set up two crossed polarizers, then insert the tank of syrup between them. Because of the optical activity of the syrup the light will be rotated and light will be transmitted by the analyzer. By rotating the analyzer to extinguish the beam, the angle of rotation can be determined. The rotation constant is equal to that angle divided by the distance the beam traveled through the syrup.

When you are finished, empty the tank and store the syrup in a covered jar. Rinse the tank and dry it to prevent a sticky mess the next time it is used.

Circuit used to measure light in polarized light experiment.

Alternate circuit is for low impedance measuring equipment. Ground pins 5 and 6 if not used.

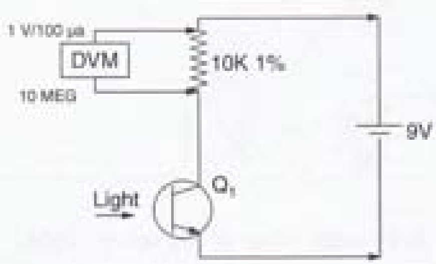
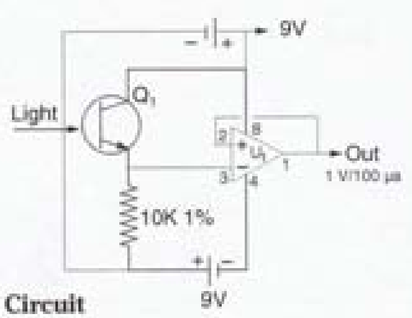


Photo Transistor Test Circuit



Alternate Circuit

Q_1 **IR Photo Transistor**
Radio Shack P/N 276-145 SDP 8403-301

U_1 **JFET OP AMP**
Radio Shack P/N 276-1715

Project #9
Birefringence of Materials:

The polarization of light can be used to control the passage of light through an optical system and to impress information on a light wave by changing (modulating) the amount of light birefringent material.

In this project the birefringence of a material will be used to change the polarization of the laser. Using a quarter-wave plate and a polarizer you will build an optical isolator. When you add a second quarter-wave plate, a polarization rotator results.

Experimental Set Up:

1. Mount a laser assembly (LA) to the rear of the breadboard. Adjust the position of the laser such that the beam is parallel to the edge and in line with a line of tapped holes in the breadboard top. Tape an index card with a small (about 2 mm) hole in it to the front of the laser, so that the laser beam can pass through it. This card will be used as a screen to monitor the reflections from the components as they are inserted in the beam. See the note in **Project #3** on the alignment of laser beams.
2. Mount a beam steering assembly (BSA-I) approximately 4 inches in from the far corner of the breadboard. Adjust the height of the mirror mount until the beam intersects the center of the mirror. Then rotate the post in the post holder until from the laser beam is parallel to the left edge and the surface of the breadboard.
3. Place a second beam steering assembly (BSA-I) in line with the laser beam about two thirds of the way along the left side of the breadboard. Rotate and adjust the mirror mount until the laser beam is parallel to the front edge and the surface of the breadboard.
4. Mount the beamsplitter in a lens chuck assembly (LCA) and place the unit four inches to the right from the last beam steering mirror. Adjust the beamsplitter such that the beamsplitter surface is oriented at 45° to the last beam steering mirror.

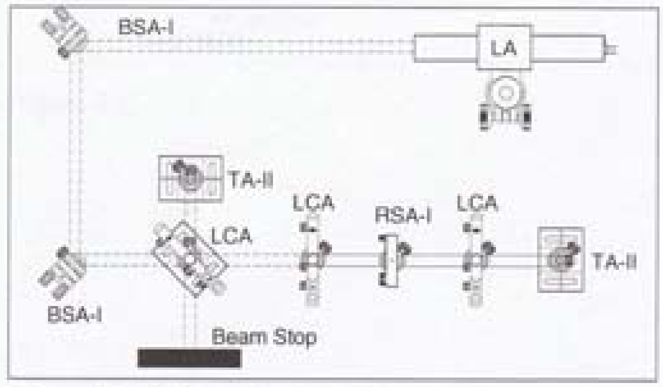


Figure 9-1. Schematic view of Birefringence of Materials experiment.

Newport Equipment Required:

Part	Catalog #.	Qty	Description
LA		1	Laser Assy
BSA-I		3	Beam Steering Assy
RSA-I		1	Rotation Stage Assy
LCA		1	Lens Chuck Assy
LCA*		2	Lens Chuck Assy without B-2 Base
TA-II		2	Modified Target Assy
FK-B2		1	Beam Splitter
		2	Linear Polarizer
		2	Quarter-wave plates

Additional Equipment Required:

Part	Catalog #.	Qty	Description
QI		2	Index Card
			Tape

Table 9.1 - Equipment Required

5. Place a piece of cardboard or some other object at the edge of the optical breadboard to block reflected light from the back surface of the beamsplitter (the back surface of a beamsplitter is always the surface opposite the beam splitting surface). There will be at least two beams of unequal intensity.

6. Place a modified target assembly (TA-II) on the opposite side of the beamsplitter. Insert a white card in the holder at the beam height. This will be used to monitor the amount of reflected light.

7. Mount a polarizer into a lens chuck assembly (LCA) without a B-2 base and mount it to the optical breadboard in line with the laser beam and several inches to the right of the beamsplitter. Set the polarizer with the indicating notch up. Rotate the lens chuck mount slightly so that the reflection off this polarizer can be seen on the index card.

8. Mount a second polarizer into a lens chuck assembly (LCA) without a B-2 base and mount it 7 inches to the right of the first polarizer. Place a second target assembly TA-II to the right of the second polarizer. Rotate the second polarizer until it completely blocks the light from the first polarizer (i.e. polarization axes crossed). Rotate the lens chuck mount slightly so that the reflection off this second polarizer can be recognized as a separate beam.

9. Insert the quarter-wave plate into a rotation stage assembly (RSA-I). Place the assembly between the two polarizers. Slowly rotate the quarter-wave plate until the output through the second polarizer is a maximum.

10. Loosen the second polarizer in its lens chuck and rotate. Note that the output does not change since the light is now circularly polarized and there is an equal component in any direction of the polarization orientation. The quarter-wave plate has converted the linear input beam to a circularly polarized beam.

11. Having verified that the plate has produced circularly polarized light, replace the second polarizer with a mirror on a beam steering assembly, BSA-I (**Fig. 9-2**). Observe the light reflections on the index card. There will be surface reflections off the surfaces of the polarizer and the quarter-wave plate, but there will be no strong reflection from the mirror because as was pointed out in **Section 0.5.2** in the Primer, the mirror reverses the circularly polarized light and on second passage through the quarter-wave plate, the beam is again linearly polarized but at right angles to the original polarization. When the reflected beam hits the polarizer again it is absorbed. You can test this by either removing or rotating the quarter-wave plate or rotating the input polarizer somewhat. In either case, the light on the mirror is no longer circularly polarized. This is equivalent to saying that the outgoing beam has been "isolated" from reflections after the quarter-wave plate.

12. Starting with the arrangement completed in Step #9 with a single quarter-wave plate in the RSA-I, hold a second quarter-wave plate between the crossed polarizers without disturbing the orientation of the first. Rotate the second quarter-wave plate until the light passing through the second polarizer is a maximum. Carefully tape this second quarter-wave plate to the RSA-I in which the first quarter-wave plate is mounted. You have now created a half-wave plate which rotates the input polarization by 90°. To check that this is indeed so, rotate the second polarizer to produce the minimum transmission. You will find that you will have to rotate through 90° and that the axes of the two polarizers are now parallel.

13. Finally, rotate the first polarizer by some specific angle, say 10°, and then note the amount by which the second polarizer must be rotated to extinguish the beam. You will find that the analyzer must rotate through twice the angle of the initial polarizer.

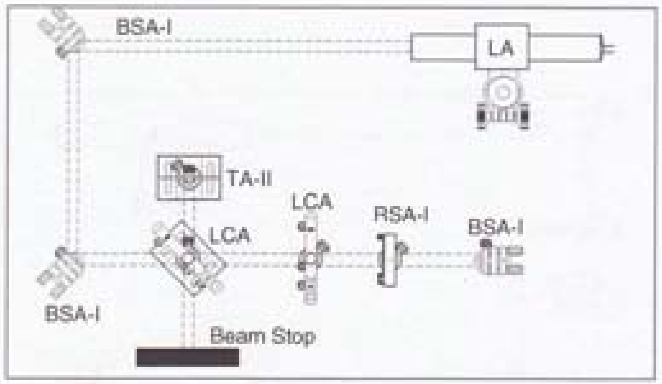


Figure 9-2.

Project #10
Abbe Theory of Imaging:

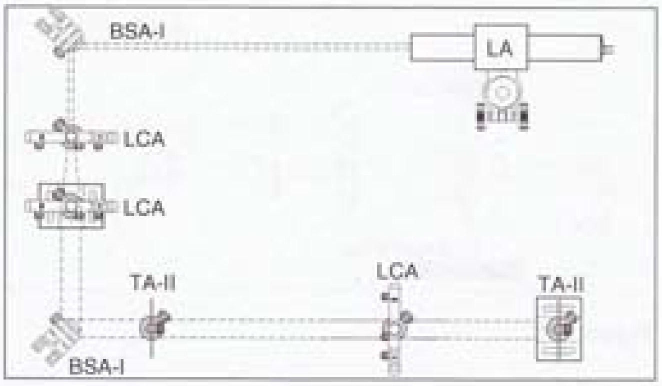


Figure 10-1. Schematic view of imaging experiment.

Newport Equipment Required:

Part	Cat. #	Qty	Description
LA		1	Laser Assy
BSA-I		2	Beam Steering Assy
LCA		1	Lens Chuck Assy
LCA*		2	Lens Chuck Assy without B-2 Base
TA-II		2	Modified Target Assy
		2	Lenses for Beam Expander
TL	KPX100	1	Transform Lens (150 mm EFL)
			Object Transparencies

Additional Equipment Required:

Part	Qty	Description
QI	1	Index card
QM	1	Microscope slide
		Toothpicks, ink, other masking materials

Table 10.1 - Equipment Required

This experiment touches on the subject of spatial frequency content of objects and how they could be used to control the shape and quality of an image. This subject is similar to finding the frequency harmonic content of a waveform such as that produced by a musical instrument. For example, a musical instrument may produce both a low pitch tone and a high pitch tone. We can control the quality of the sound by filtering out one of the two frequency harmonics with a low pass or a high pass filter. A discussion of the basic theory was given in **Section 0.7** in the Primer.

As noted in the Primer, objects have certain intensity profiles which translate into a corresponding spatial frequency distribution. In this project the frequency distribution of an object illuminated with a laser beam will be examined with a single lens placed after the picture or slide. The light distribution formed at that focal plane tells us the frequency content of the object, and by manipulating the light in that plane we gain control of the quality and content of the image to be displayed.

The laser beam we are using has a smooth profile, i.e. the intensity distribution does not have any wiggles, and when it is focused it produces a single small spot, i.e. the original beam contains only low spatial frequencies. On the other hand, if we pass this beam through a grating or screen which introduces many variations on the laser profile, then in the focal plane of the lens we will see several spots indicating that additional spatial frequency components have been added. Let us build a set up that allows us to examine this feature.

1. Mount a laser assembly (LA) to the far side of the breadboard (**Fig. 10-1**). Adjust the position of the laser such that the beam is parallel to the edge and in line with a line of tapped holes in the breadboard top. Tape an index card with a small (about 2 mm) hole in it to the front of the laser, so that the laser beam can pass through it. This card will be used as a screen to monitor the reflections from the components as they are inserted in the beam. See the note in **Project #3** on the alignment of laser beams.

2. Mount a beam steering assembly (BSA-I) approximately 4 inches in from the far corner of the breadboard. Adjust the height of the mirror mount until the beam intersects the center of the mirror. Then rotate the post in the post holder until from the laser beam is parallel to the left edge and the surface of the optical breadboard.

3. Place a second beam steering assembly (BSA-I) in line with the laser beam at the lower left corner of the optical breadboard. Rotate and adjust the mirror mount until the laser beam is parallel to the front edge and the surface of the optical breadboard.

4. Set up a beam expander between the first two BSA-I's as explained in **Project #3**. Mount the first lense to the optical table without a B-2 base (Fig 10-1).

5. Mount the 150mm EFL transform lens in an LCA without a base 12 inches from the second BSA-I and center it in the path of the beam.

6. Set up a modified target assembly (TA-II) with an index card and place it at the beam focus, 150 mm from the transform lens. The plane of the card represents the back focal plane of the lens. For some of the experiments the index card will be replaced by a microscope slide.

7. Mount a second modified target assembly (TA-II) without a base 225 mm before the transform lens. This assembly will be used to hold the picture slides before the transform lens in the path of the laser light. This assembly will be called the slide holder.

8. The set up is now ready for the examination of slides. The image will be observed on an index card in another modified target assembly. The location of the observation plane will be about 450 mm after the last lens and will give an image about twice the size as the object slide when the card at the back focal point of the lens is removed.

9. Remove any slides attached to the slide holder. At the back focal plane we see a single focal spot. The position of the spot locates the "dc level" of illumination of the beam entering the lens. Any other spots appearing on the card indicate that other spatial frequencies are present. Remove the card from the back focal plane and you will see uniform (or dc level) illumination at the observation place.

10. Place the target containing the square mesh in the slide holder and replace the index card to the back focal plane of the lens. There you will see a square grid pattern of dots representing the frequency content of the mesh in both horizontal (or *x*) and the vertical (or *y*) axes. Mark on the card with a pencil the location of these axes. The dots on the *x* (or *y*) axis represent frequencies present in that direction in the slide.

11. Remove the card at the back focal plane and move the TA-II in the image plane to achieve the sharpest image. This image can be manipulated by eliminating certain frequencies, much in the same way a high fidelity audio filter controls the tone of a musical instrument. To illustrate this, cut out a narrow vertical slit in a section of the index card such that only those dots on the horizontal axis are passed through the cutout. Place the card in the TA-II at the back focal plane so that the rest of the dots are blocked by the card. Examine the image on the index card in the observation plane and record what you see. You will note that the image consists of only horizontal lines. When you remove the slit in the focal plane, the image will resemble the original object.

12. Rotate the card in Step #11 above such that the dots on the y-axis are passed. Record what you see.

13. Make another cut out such that only the central spot is transmitted. Note that only uniform illumination is present at the observation plane, i.e. you have filtered out all higher frequencies and all that is left is the low frequency (i.e. relatively uniform illumination). This is the principle of the spatial filter. It "cleans" optical beams by removing the high frequencies by focussing the beam through a pinhole, thereby obstructing the unwanted harmonics.

14. Other cutouts can be inserted at the back focal plane. For example, if you make a filter in the form of a larger hole that passes only the central and the two adjacent spots. Record what you see. Note that this removes the sharp edges of the image and produces a soft picture. Alternately, you can make a special filter that will obstruct only the central spot by putting a dot of ink on a microscope and locating it at the center spot in the back focal plane. Record your observations. This will remove the uniform illumination from the image and leave the edges enhanced.

15. Replace the square mesh slide at the slide holder with any picture slide. Notice that this picture has superimposed on it many horizontal lines. At the back focal plane of the lens the light distribution consists of an irregular distribution of light representing the many spatial frequencies present in the picture. Superimposed on this distribution is a set of faint spots aligned along the vertical axis and passing through the central spot. This line of spots represent the frequency content of the horizontal lines in the picture slide.

16. Attach with tape to the microscope slide two pins (or toothpicks or thin objects) so that when it is placed back in the back focal plane the objects will obstruct this vertical line of spots. The central spot should not be obstructed. Record your observations. Remove and then replace this "needle" filter.

17. Other cutouts may be made and used at the back focal plane. For example, cut a hole in the index card so that it obstructs the outer spots. These spots contain the high frequency information. Record your observations. Obstructing them leads to a softer, more fuzzy, picture as is seen at the observation plane.

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