

Reflection, Refraction and Polarization

INTRODUCTION

Refraction

When a *ray* of light strikes the surface of a piece of transparent material the beam is split—part of the beam is reflected from the surface, while the rest is transmitted into the material. Experiment has shown (and will show again in this lab) that the angle of the reflected light is equal to the angle of the incident light (both angles are conventionally measured with respect to a line normal to the surface). For the transmitted ray, the path the light takes is bent as it passes from one medium into another. This bending of the light ray is known as *refraction*.

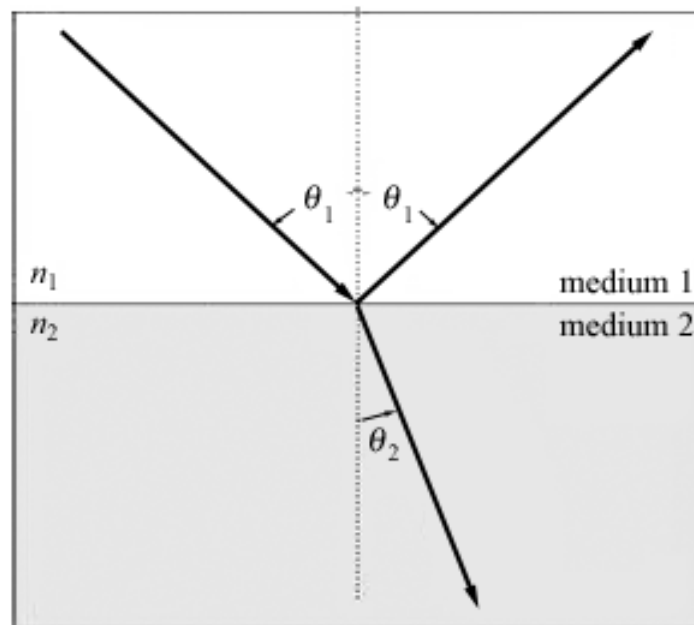


Figure 1

The angle of the refracted ray is related to the angle of the incident ray (see Fig. 1) by Snell's Law:

$$n_1 \sin \theta_1 = n_2 \sin \theta_2 \quad (1)$$

where n_1 and n_2 are the index of refraction of medium 1 and medium 2, respectively. The index of refraction of a material is defined to be the ratio of the speed of light in vacuum to the speed of light in the material, $n = c / v$. The index of refraction of air varies only slightly ($< 0.03\%$) from one, and for this experiment is taken to be one, i.e. $n_{\text{air}} = 1$.

Total Internal Reflection

If light passes from one medium into another medium of smaller n , the angle of refraction will be larger than the angle of incidence. At the critical angle of incidence, θ_c , the angle of refraction will reach 90° . The “transmitted” light is not transmitted into the second medium, but travels along the boundary of the two media, parallel to the surface (see Fig. 2).

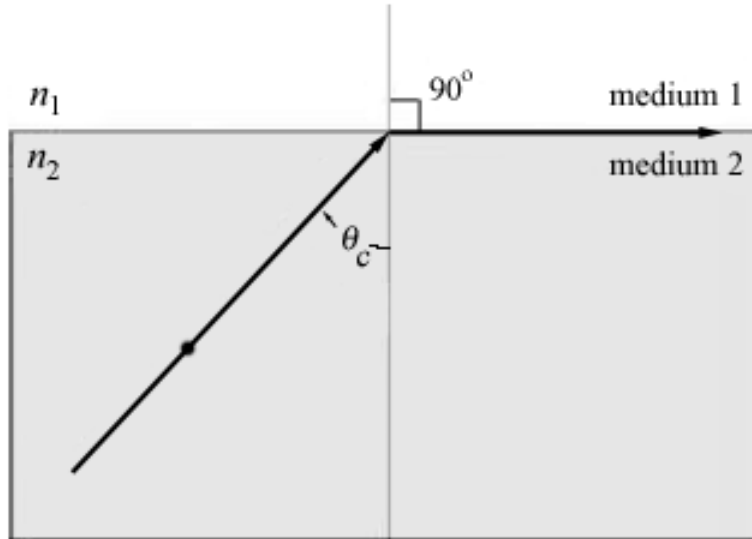


Figure 2

For incident angles greater than the critical angle, all the light is reflected back into the first medium, this condition is known as total internal reflection. Since the critical angle is just the angle for which the refraction angle is 90° , we have $\sin \theta_1 = \sin 90^\circ = 1$. Eq. (1) gives the following equation.

$$\sin \theta_c = \frac{n_1}{n_2} \tag{2}$$

Polarization by Reflection: Brewster’s Angle

When an unpolarized light beam is reflected from a surface, the reflected beam will become partially polarized depending on the angle of incidence. For one particular angle of incidence, called *Brewster’s angle*, θ_B , the reflected beam is completely polarized. The condition for this phenomenon to occur is shown in Fig. 3. The polarization of the incident beam can be described by two electric field components, one parallel to the surface (represented by dots) and the other perpendicular to the first component and to the direction of propagation (represented by arrows). At Brewster’s angle of incidence, the angle between the reflected and refracted beams is 90° . The reflected beam is completely polarized, with its electric field parallel to the surface. Brewster’s angle can be related to the index of refraction of the reflecting surface by using Snell’s law. Substitution of $\theta_1 = \theta_B$, $n_1 = n_{\text{air}} = 1$, and $n_2 = n$, into Eq. (1), we get $\sin \theta_B = n \sin \theta_2$. Because $\sin \theta_2 = \sin(90^\circ - \theta_B)$, the expression for n above can be written as the following equation.

$$n = \frac{\sin \theta_B}{\cos \theta_B} = \tan \theta_B \quad (3)$$

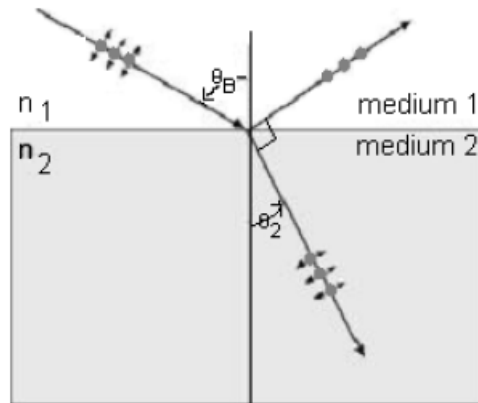


Figure 3

Laser Safety Guidelines

The entry of even a very weak laser beam into the eye can cause partial or complete loss of sight in that eye. The risk is present even for stray reflections off optical surfaces. Always handle lasers in a safe manner, regardless of the output power.

- Use a shield to constrain the laser beam from entering another lab group's area.
- Ensure the laser beam (including stray reflections) is constrained to one level (well below eye level). Always remain standing; do not crouch down to this level.
- Remove all reflective surfaces from the laser area (including wristwatch faces and similar objects); securely mount all optics.
- Do not look at the laser beam from within the beam.
- The laser should not be pointed at any person (especially at their eyes).

Guidelines from: Power Technology, Inc.¹ (7/23/2002).

PROCEDURE

The apparatus for this experiment (shown in Fig. 4) consists of a He-Ne laser light source, an optics bench, a ray table and ray table base, an acrylic semi-circular disk, a ray table component holder, and a polarizer. Although the power of the laser is quite low (< 1 mW), it is advised that you **follow the laser safety guidelines**.

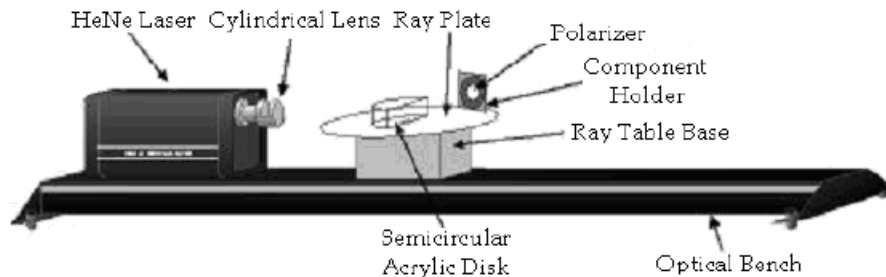


Figure 4

The beam produced by the laser is too narrow for this experiment. Thus a cylindrical dispersion lens is mounted in front of the laser (see Fig. 4). As shown in Fig. 5, the lens has a focusing effect and beyond the focal point it disperses the light on a plane perpendicular to the axis of the cylindrical lens.

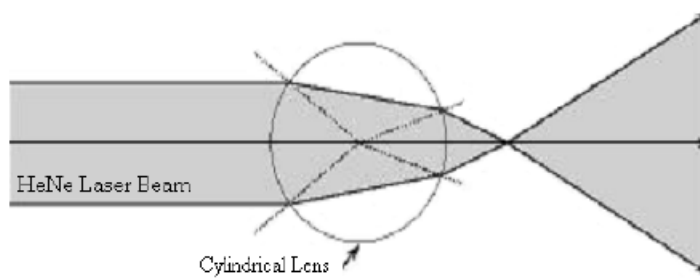


Figure 5

Part 1: Snell's Law and Index of Refraction - Data

In this part of the experiment you will study the reflection and refraction of light from a plane separating two media (air and acrylic). You will verify that the path of the refracted light satisfies Snell's law and as a result, you will derive the index of refraction of acrylic.

- 1 Place the He-Ne laser near one end of the optics bench. Plug in and turn on the laser.

CAUTION: Follow the Laser Safety Guidelines.

- 2 Place the cylindrical dispersion lens on the laser. Adjust the height of the cylindrical lens so that the laser beam crosses the central axis of the cylinder. If this adjustment is done properly, you will see the laser beam spread out into a thin uniform line on a distant surface (such as a wall or a piece of paper held vertically at a distance). Rotate the cylindrical lens until the line is vertical. *Note that because the laser light is spread out vertically, it may not be entirely below eye level.*
- 3 Place the ray table base on the optics bench about 15 cm from the laser. Mount the ray table on the base.

- 4 Place the acrylic semi-circular disk on the ray table with the flat side facing the laser and lying on the line labeled “COMPONENT”.
- 5 Center the disk on the ray table by sliding the flat side parallel to the “COMPONENT” line until a ray incident at 0° is refracted at an angle of 0° .
- 6 Rotate the ray table so that the ray is now incident at some angle with respect to the normal. Check if the reflected ray makes the same angle with the normal. If not, rotate the disk slightly to obtain the same angle.
- 7 Repeat steps 6 and 7 until you are satisfied that the disk is properly positioned on the ray table.
- 8 By rotating the ray table clockwise, set the angle of incidence to each of these settings 0° , 10° , 20° , 30° , 40° , 50° , 60° , 70° , and 80° . For each angle of incidence, measure and record the angle of refraction, refraction_1 . Check the alignment of the disk before each measurement. What difficulties did you encounter in measuring the angle of refraction for large angles of incidence ($> 70^\circ$)?
- 9 Repeat the measurement in step 8 for refraction_2 , this time rotating the ray table counterclockwise.

Part 2: Internal Reflection - Data

In this part of the experiment, you will observe that light cannot pass from a medium (acrylic disk) into another medium (air) with a lower index of refraction if the angle of incidence is greater than the critical angle, given by Eq. (2). The light is totally reflected back into the medium. You will measure the critical angle of the acrylic disk and use Eq. (2) to determine its index of refraction.

- 1 Set up the acrylic disk as in Part 1. Rotate the ray table so that the light ray hits the circular side of the disk first. In this way the ray will approach the flat side of the disk from the acrylic side and exit on the side with air (lower index of refraction) (see Fig. 6).

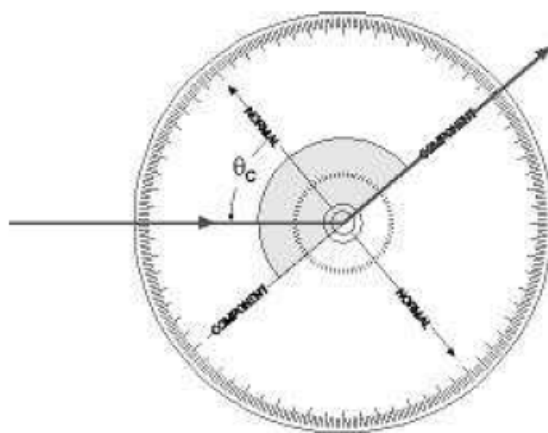


Figure 6

- 2 Starting from a small angle of incidence (near 0°), gradually increase the angle by rotating the ray table clockwise. Record any changes in the reflected and transmitted ray as you increase the angle of incidence. Report your observation in the discussion section of your lab report.
- 3 As the incident angle approaches the critical angle, the refracted ray will approach the flat side of the disk. Determine the angle when the refracted ray *just* disappears and record the angle as θ_{c1} . Without moving the acrylic disk, repeat the measurement (θ_{c2}), this time rotating the ray table counterclockwise.
- 4 Estimate the uncertainty in your measurement of θ_c .

Part 3: Polarization by Reflection: Brewster's Angle - Data

In this part of the experiment, you will observe that light is polarized when reflected off a surface, in this case the flat side of the acrylic disk. At Brewster's angle of incidence, the polarization is complete, with the electric field vector of the light parallel to the surface. You will measure Brewster's angle and derive the index of refraction of the acrylic disk using Eq. (3).

- 1 Set up the acrylic disk as in Part 1. Slowly rotate the ray table clockwise until the angle between the refracted and reflected rays is 90° (see Fig. 7). Record the angle of incidence as θ_{B1} . Without moving the acrylic disk, repeat the measurement (θ_{B2}), this time rotating the ray table counterclockwise.
- 2 Estimate the uncertainty in your measurement of θ_B .

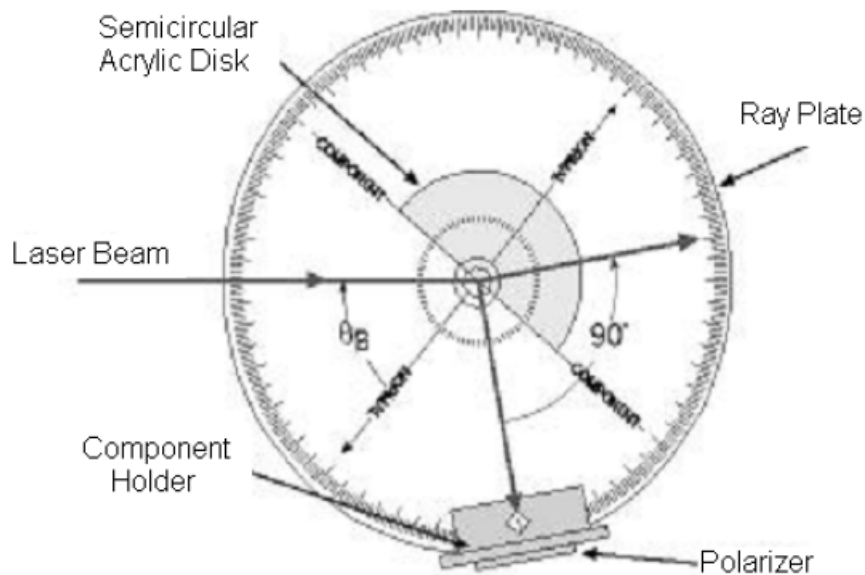


Figure 7

- 3 Attach the polarizer to the ray table component holder and set it up on the ray table so that it is in line with the reflected ray (see Fig. 7). Observe the intensity of the light that passes through the polarizer on a viewing screen as you rotate the polarizer. If the polarizer does not rotate easily, the effect can be observed by simply holding and rotating the polarizer with your hand.

CAUTION: Do not look directly into the laser.

- 4 Is the reflected light plane polarized? If so, at what angle from the vertical is the plane of polarization? Change the incident angle so that it is not equal to Brewster's angle and check if the reflected light is still plane polarized.

DATA ANALYSIS

Part 1: Snell's Law and Index of Refraction - Analysis

In this part of the experiment, you will analyze the data from Table 1 to verify if Snell's Law is satisfied and if so, derive the index of refraction of acrylic. Since we are approximating the index of refraction for air by $n_{\text{air}} = 1$, Snell's law when applied to our experimental setup reduces to:

$$\sin \theta_1 = n \sin \theta_2 \quad (4)$$

where θ_1 is the angle of incidence, θ_2 is the angle of refraction, and n is the index of refraction of acrylic. Thus, if we make a graph of $\sin \theta_1$ vs. $\sin \theta_2$, we should get a straight line if Snell's Law is satisfied, and the slope of the straight line will be the index of refraction.

- 1 Make a plot of $\sin \theta_1$ vs. $\sin \theta_2$ using the data from Table 1, refraction₁.
- 2 Use the linear least square fit to find the value of the index of refraction and its uncertainty.
- 3 Repeat the analysis for refraction₂.
- 4 Take the weighted average of the two values of the index of refraction, n_1 (from refraction₁) and n_2 (from refraction₂) by using the formula: $\bar{n} = w_1 n_1 + w_2 n_2$. The weights w_1 and w_2 are taken to be proportional to the inverse of the square of the uncertainty of each n respectively. In this way the value of n with the smaller uncertainty will be given more weight. Thus,

$$w_1 = k \frac{1}{u_1^2} \text{ and } w_2 = k \frac{1}{u_2^2} \quad (5)$$

where the proportionality constant, k , is chosen to normalize the weights, so that $w_1 + w_2 = 1$. The value of k is given by the following equation.

$$k = \frac{1}{\frac{1}{u_1^2} + \frac{1}{u_2^2}} \quad (6)$$

- 5 Calculate w_1 and w_2 and check if $w_1 + w_2 = 1$. Calculate the weighted average of n .
- 6 Calculate the uncertainty of the average value of n using the formula: $u = \sqrt{k}$.

Part 2: Critical Angle - Analysis

- 1 Determine the critical angle for acrylic by averaging the values of θ_{c1} and θ_{c2} .

- 2 How does averaging the results of the measurements taken by rotating the ray table in alternate directions improve the accuracy of the result?

Use Eq. (2) to find the index of refraction for acrylic from the critical angle. Show that the following is true.

$$n = \frac{1}{\sin \theta_c} \quad (7)$$

Use the upper-lower bound method to determine the uncertainty in n_{crit}

Part 3: Brewster's Angle - Analysis

- 1 Determine Brewster's angle θ_B for acrylic by averaging the value of θ_{B1} and θ_{B2} .
- 2 Use Eq. (3) to find the index of refraction for acrylic from Brewster's angle.
- 3 Use the upper-lower bound method to determine the uncertainty in θ_B .

DISCUSSION

Summarize the index of refraction derived from Parts 1, 2, and 3. Compare your results with the value of 1.49 for the index of refraction for acrylic. Which of your measurements is most precise? Which is most accurate?

In performing Part 1, what difficulties did you encounter in measuring the angle of refraction at large angles of incidence? How would you take this problem into account in the analysis of your data? Are your graphs consistent with Snell's Law? Explain. Are your results for the two sets of measurements (refraction₁ and refraction₂) the same? If not, to what do you attribute the differences?

In Part 2, describe the changes in the intensities of the reflected and refracted rays as the angle of incidence approaches the critical angle.

In Part 3, describe the change in polarization of the reflected ray as the angle of incidence approaches Brewster's angle.