Experiment 3

Re°ection and Refraction of Light { Planar Surfaces

1 Introduction

In this series of experiments we shall study the phenomena of re°ection and refraction of light from planar surfaces. We will determine Snell's law and the law of re°ection experimentally. We will do this by investigating refraction at interfaces, refraction through a prism and total internal re°ection. Throughout this experiment, we will employ the geometrical optics approximation to analyze the behavior of light.

Please take care while making your measurements. You will use a laser in this experiment! Be careful not to shine it into your or your neighbor's eye! Always know where your beam is directed!

2 Theory

When an optical ray encounters a boundary between two transparent media, usually part of the light is re°ected from the boundary and part enters the second medium. Consider the situation depicted in Fig. 1. Two transparent media along with their interface are shown. Each medium is characterized by a dimensionless parameter called the index of refraction, designated by n_1 and n_2. A light ray is incident from the left in medium 1 and strikes the interface of the two media at an angle ® with respect to the normal to the surface. The transmitted ray propagates in a di®erent direction than that of the incident ray. This change in direction is called refraction. The angles of the re°ected and refracted rays are determined by the following laws:

1. The angle of incidence, ®, is equal to the angle of re°ection.

2. The angles of incidence and refraction are related by

$$n_1 \sin\alpha = n_2 \sin\beta; \tag{1}$$

known as Snell's law.

3. The re°ected and refracted rays lie in a plane de¯ned by the incident ray and the normal to the interface at the point of incidence.

For normal incidence, the amount of light re°ected at the interface is given by

$$R = \left(\frac{n_2 - n_1}{n_2 + n_1} \right)^2 : \tag{2}$$

The quantity R is called the re°ectance. For an interface between air and glass $R \approx 0.04$ for visible light. See Ref. 2 for a derivation of this formula.

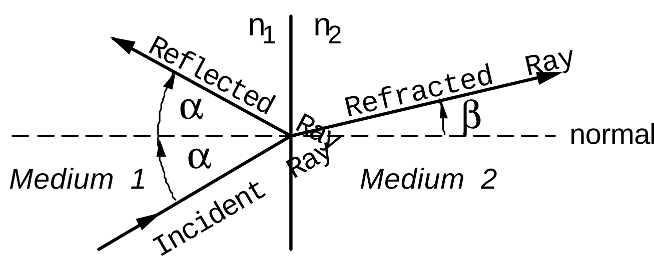

Figure 1: Re°ection and refraction of light from an interface.

3 Experiment

3.1 Re°ection and Refraction of a Glass Block

In this part of the experiment, we will study re°ection and refraction with a block of glass (1) to demonstrate Snell's law, Eq. (1), and the law of re°ection and (2) to determine the index of refraction, $n_p = n_2/n_1$, of the glass relative to the lab air.

Use a laser beam as your source to generate rays for the setup in Fig. 2. To determine the angles of re°ection and refraction, insert pins into the paper through the center of the beam to locate the rays as shown in the ¯gure. **Note, the order in which you place the pins is important.** First, place a clean sheet of paper on the cork board. Next, place the laser at the position of the eye in the ¯gure. Locate the position of the beam by placing pin (6) on the paper behind where the block will be placed, along the dashed line near the label S.

Note, pin (6) is not shown on the ¯gure! Now place the glass block on the paper at an angle with respect to the laser beam and trace its perimeter with a sharp pencil. Next locate the rest of the pins as shown in the ¯gure in the following order: (4), (3), (5), (1) and (2). Remove all the pins and the block and join all the pin holes with appropriate pencil lines and determine angles ® and ¯, S, the lateral shift between the incident and emergent rays, and the uncertainties in these quantities. Repeat this procedure for four to six angles.

Some things to think about before you start. The sine function is very nonlinear, you should estimate what angles to use to spread your points out evenly. You will need to estimate the uncertainty in your measurements of the angles. You should consider how well you can locate the beam. Note, part of the uncertainty that in°uences your measurements is due to the width of the laser beam; a conservative estimate of the uncertainty with which you can locate a pin is approximately the half-width of the laser beam. You should also consider what a®ect the size of the angle has on the uncertainty of the measurement. It would be a good idea to repeat your series of measurements as a consistency check.

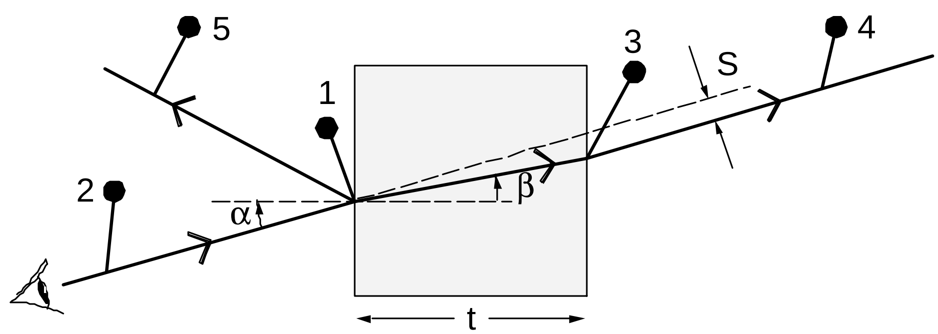

Figure 2: Five of the pin positions used to explore the laws of re°ection and refraction. Pin number 6 should be placed along the dashed line near the S.

3.1.1 Analysis

First, show that the angle of incidence is equal to the angle of re°ection. There are a variety of ways you might do this. One example would be to plot ®$_{inc}$ vs ®$_{ref}$ and show that a 45$^{\pm}$ line ¯ts the data. You should place error bars on your data, in both the x and y directions. An alternative method is to plot ®$_{inc}$ ¡ ®$_{ref}$, or visa versa, and show that your data fall on a straight line with zero slope. Again, include error bars. How well do either of these lines represent your data? Use one of these methods or one of your own design to deo the analysis.

Some things to think about. Should the 45± or 0± line go through the origin? How con¯dent are you that your data is consistent with the two angles being the same.

Second, show that Snell predicts the angles ® and ¯ that you measured. This can be done by plotting sin ® vs sin ¯ and ¯tting the result to a straight line. If sin ¯ is plotted along the x-axis, Eq. (1) implies that the slope will be n_2=n_1. Determine the index of refraction of the glass.

Finally, show that your data is consistent with Snell's law through the following equation:

$$S = t \sin ® \ \text{µ} \ 1 \ ¡ \ \frac{\tan ¯}{\tan ®} \ \text{¶} \ ; \qquad (3)$$

where t is the thickness of the block, as noted in Fig. 2. Do this by calculating S and it uncertainty from your measurements of ® and ¯ and compare it to your measured S and its uncertainty. If you eliminate ¯ in favor of ® in Eq. (3) you can plot S vs ® and show that the calculated S lies between the limits of your measured S.

3.2 Total Internal Re°ection With a Semi-Circular Block

In this series of measurements, you will consider light incident from a medium of higher index of refraction to one of lower index of refraction. As the incident angle increases from 0± ¡ 90±, you will reach a point where no light is transmitted into the medium of lesser n. This particular angle of incidence is called the critical angle for total internal re°ection, $µ_{tir}$, and will occur for incident µ < 90±. For incident angles larger than the critical angle, all of the light is re°ected back into the incident medium at an angle equal to the incident angle. The critical angle is given by:

$$\sin µ_{tir} = \frac{n_o}{n_{tir}} \qquad (4)$$

where $n_{tir} > n_0$. At $µ_{tir}$, Fig. (3) show that the angle of refraction is 90±.

Use the semi-circular glass block and determine $µ_{tir}$,. Place the block °at on the prism holder and place them both on the rotating table. Next, adjust the height of the rotating table so that the laser light hits the glass block. Adjustments should be made so that the incident laser beam travels along a radius of the glass block. One way to insure that your beam is positioned correctly is to retro-re°ect the beam from both surfaces. That is, make the beam re°ect back onto itself. Once in place, you can rotate the table and measure both the incident, ®, and refracted, ¯, angles. Do this for four to six angles to determine the critical angle of the glass block. Remember to estimate the uncertainty with which you can measure these angles. Now plot sin ¯

vs sin ®, and determine n_{tir} and its uncertainty from the slope of the linear ¯t. Use the ¯t parameters to determine $µ_{tir}$ and its uncertainty. Determine $µ_{tir}$ directly by locating the angle at which the transmitted light vanishes. Estimate the uncertainty with which you are able to determine $µ_{tir}$. Compare the two results. Does your measured result for $µ_{tir}$ agree with that derived from Eq. (4)? Remember, you do not know n_{tir} exactly either!

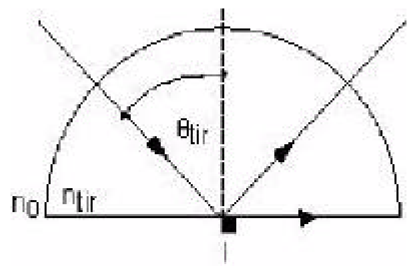

Figure 3: Semi-circular block showing the path of a light ray at the onset of total internal re°ection.

3.3 Minimum Deviation Angle in a Prism

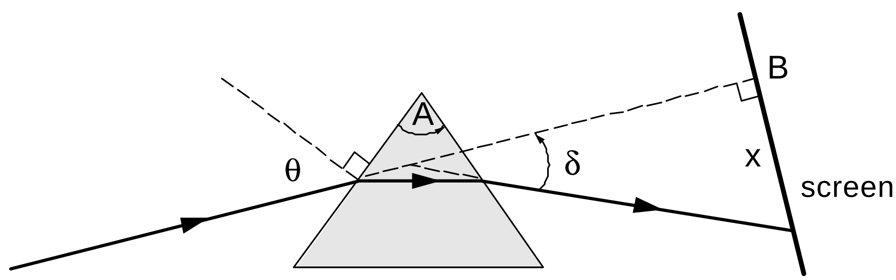

Figure 4: A beam of light shown incident on a prism at an angle µ and ejected with a deviation angle ±. The deviation angle can be determined by the linear distance x on a screen a short distance away from the prism.

In Fig. 4, there is an illustration of a prism and the path of a light ray through the prism. A beam of light will be deviated through an angle ±. In this case, light is refracted through two surfaces that are not parallel so the deviation is much larger what you saw in the ¯rst part of this experiment. At a certain incident angle, $µ_m$, the deviation will be at its minimum value of $±_m$ given by

$$±_m = 2µ_m \text{ ¡ } A: \quad (5)$$

Using Snell's law, one can show that the index of refraction of the prism is given by

$$n_{ang} = \frac{\sin \mu_m}{\sin(A{=}2)}: \quad (6)$$

Determine n_{ang} of the prism by measuring μ_m and A.

To determine μ_m, proceed as follows. Place the prism on the rotating table. Then, rotate the table so that the incident laser beam re°ects back along itself after it has struck a side of the prism. Here, the incident angle is zero. Record the angular scale reading. As you rotate the table to di®erent angles you will observe the beam move in one direction along a screen behind the prism. Eventually, the movement will cease. As you continue to change the angle in the same direction the beam moves again but in the reverse direction. The angle where the beam movement stops is where the deviation, ±, is minimized. Record the angle at this point. To estimate the uncertainty in this angle, you will notice that you are able to rotate the table a bit with no discernible movement of the beam on the screen. This angular movement together with your ability to read the scale will comprise your uncertainty. To measure A, you should retro-re°ect the laser beam o® a side of the prism adjacent to angle A. Then, you should rotate the table to achieve retro-re°ection from the other side adjacent to A. The angle through which you rotated the table is equal to $180^{\pm}$ ¡ A. To help improve your uncertainty in this measurement you should make more than one measurement of μ_m and A.

Things to keep in mind when using the rotating stage. Hysteresis. There will be hysteresis in the rotation stage so be sure to always rotate the stage in the same direction when taking measurements.

Bibliography and Further Reading:

1. Born, M., and Wolf, E. Principles of Optics, 6th ed. Oxford: Pergamon Press, 1980. Chapters III and IV.

2. Hecht, E., and Zajac, A. Optics. Reading: Addison-Wesley, 1974. Chapters 2 and 3.

3. Klein, M. V. Optics. New York: John Wiley & Sons, 1970. Chapters 4 and 5.

4. O'hanian, H. Physics. New York: W. W. Norton, 1985. Chapter 37.