Experiment 5

Snell's Law

5.1   Objectives

- Use Snell's Law to determine the index of refraction of Lucite.

- Observe total internal reflection and calculate the critical angle.

- Explain the basis of how optical fibers work.

5.2   Introduction

We often overlook the phenomenon of light refraction. We take for granted that when we dip a spoon into water, it appears to bend or shift position. The reason is actually quite fascinating, since it depends on the changing velocity of light in the water. Using this knowledge, you will be better equipped to predict how far underwater an object is, depending on its apparent depth.

5.3   Key Concepts

As always, you can find a summary on-line at Hyperphysics[1]. Look for keywords: index of refraction

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[1]http://hyperphysics.phy-astr.gsu.edu/hbase/hph.html

There is also a simulation of the phenomenon that you are encouraged to play with[2].

5.4   Theory

A beam of light traveling in a medium with index of refraction n_1 that is incident at an angle θ_1 on the surface of another medium with index of refraction n_2 will be bent to a new angle θ_2 according to Snell's Law,

$$n_1 \sin \theta_1 = n_2 \sin \theta_2. \tag{5.1}$$

An illustration of this is found in Fig. 5.1.

Total internal reflection is an application of Snell's Law. It's called "total" internal reflection because normally, part of the light is reflected and part transmitted through refraction. In *total internal reflection*, no light is transmitted; instead, all is reflected and remains internal to the material.

Consider Snell's law for light inside the Lucite block, which strikes an outer surface, surrounded by air. Then $n_1 = 1.55$, $n_2 = 1.00$, and θ_1 is the angle from the normal at which the light strikes the surface. Snell's Law indicates that $\theta_2 > \theta_1$. But as θ_1 becomes larger, there will come a time when θ_2 has already reached 90°, and can't become any larger and
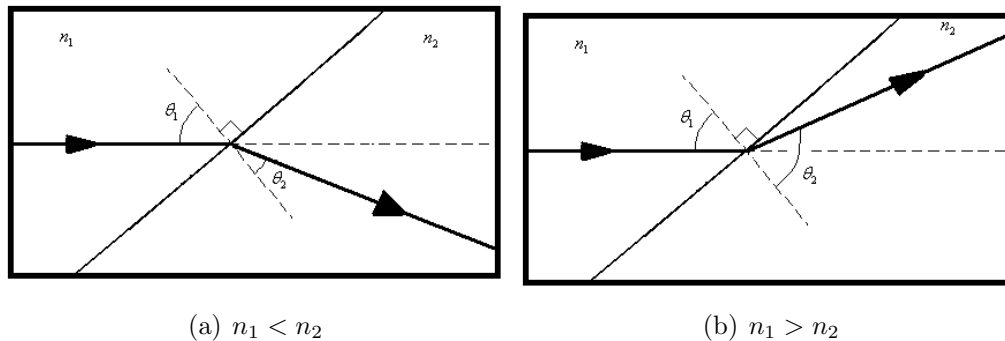
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[2]http://phet.colorado.edu/en/simulation/bending-light

(a) $n_1 < n_2$ (b) $n_1 > n_2$

Figure 5.1: Light passing through an interface between mediums of differing indices of refraction.

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$\sin \theta_2 = 1$. We call the incident angle here the *critical angle*, θ_C, the smallest angle that creates total internal reflection. Inserting $\theta_1 = \theta_C$ and $\sin \theta_2 = 1$ into Eq. 5.1 and solving for the critical angle, we find

$$\theta_C = \arcsin \left(\frac{n_2}{n_1} \right) \tag{5.2}$$

Optical fibers use this phenomenon to efficiently transmit light directed along the axis of the fiber. Such light has a very shallow angle with respect to the inner surface of the fiber. Thus, θ_2 is near 90°, which is above the critical angle, so it will be totally internally reflected, provided that the outer surface of the fiber is very smooth. The smoothness guarantees that there are no jagged corners where light can make a larger angle with the surface and escape through refraction.

5.5 In today's lab

Today you will be using refraction of a laser to determine the index of refraction of Lucite, a plastic that is often used as a lighter or safer alternative to glass. You will also find the critical angle at which total internal reflection happens.

5.6 Equipment

- optics bench

- laser on mount

- protractor on mount

- half-disk of transparent Lucite block

- screen on mount

- paper to attach to screen

The apparatus consists of a laser, a semi-cylindrical piece of Lucite ($n = 1.55$) mounted on a protractor, and a screen. The schematics of the set up are shown in Fig. 5.2. Notice that the laser strikes the curved cylindrical surface first and passes through the center of curvature of this surface. Therefore, the angle of incidence of this first surface is 90°, and by Snell's Law, no change of direction of the light ray occurs at this first interface.
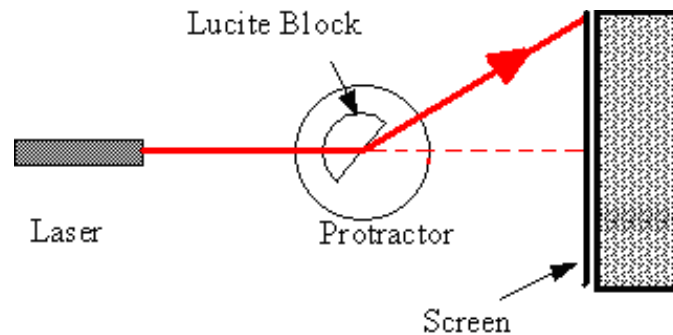
Figure 5.2: Schematic of experimental setup.

Safety Tips

The laser is a device that can produce an intense, narrow beam of light at one wavelength. NEVER look directly into the laser beam or its reflection from a mirror, glass, watch surface, jewelry, etc.

5.7 Procedure

Setup and calibration

1. Turn on the laser. **WARNING: Never look directly into the laser or its light reflected from a mirror, glass surface, the Lucite block, etc.**

2. Adjust the protractor's height so that the laser strikes the Lucite block at its midpoint.

3. Remove the Lucite block from the protractor.

4. Set the screen about $20\,\mathrm{cm}$ beyond the center of the protractor. The center of the protractor is marked as "+". Record this distance (labeled as x in Fig. 5.3) in your spreadsheet.

5. Rotate the laser so that the light passes through the protractor's axis of rotation. Use a ruler or sheet of paper placed with its edge on the axis (marked with a "+" on the protractor) to shine the laser on, to
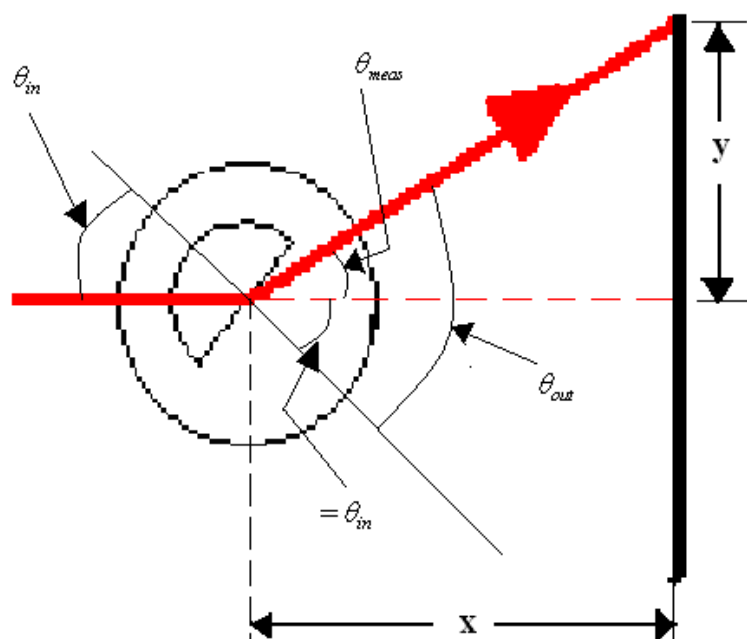
Figure 5.3: Schematic of setup with variable labels.

help locate the correct angular orientation of the incoming laser light. Mark the laser location where the laser light strikes the screen.

6. Return the Lucite block to the protractor. It fits in two orientations, and only one is correct. It is very important that the flat edge of the semi cylindrical block passes through the protractor axis of rotation. This will happen when it is aligned with one of the lines of the "+" sign marking the axis of rotation.

7. To measure angles, we want a protractor setting of 0° to correspond to the case when the light is normally incident to the back (flat surface) of the Lucite block. When this occurs, the light will not change direction as passes from the Lucite back into the air. Adjust the protractor to 0° (the silver arrow should be pointing at 0°). Now rotate the protractor's base until the center of the light spot on the screen coincides with the location you marked in Step 5. Notice the light spot is significantly

larger than it was when the laser light did not pass through the Lucite block; suggest a possible explanation (this is Question 3).

The laser light is now normally incident on both surfaces of your Lucite block and the apparatus is properly calibrated.

Determination of index of refraction of Lucite

1. Vary in angle of incidence (θ_{in}) in increments of 5° by rotating the protractor. The angular reading on the protractor is θ_{in}.

2. Place a mark on the screen where the light strikes the screen for each of the incident angles. The location of the light on the screen is labeled as y in Fig. 5.3.

3. After marking the locations of all of your refracted rays on the screen, remove the screen and measure their locations (y). Record these locations in your spreadsheet.

4. Using the distance from the block to the screen, x, and the distance that the light is deflected, y, you can find an angle θ_{meas}, using the relationship

$$\theta_{\text{meas}} = \arctan\left(\frac{y}{x}\right) \tag{5.3}$$

5. The refracted angle, θ_{out}, is related to θ_{in} and θ_{meas} by

$$\theta_{\text{out}} = \theta_{\text{in}} + \theta_{\text{meas}} \tag{5.4}$$

6. Use Excel to calculate θ_{meas} and θ_{out}. The Excel formula for arctan is `=(180/pi())*atan(CELL1/CELL2)`. The `(180/pi())` is necessary to convert the arctan result from radians to degrees.

7. Have Excel calculate $\sin\theta_{\text{in}}$ and $\sin\theta_{\text{out}}$. Use `=sin((pi()/180)*CELL3)` to calculate sin in Excel.

8. Import your data into Kaleidagraph and make a graph of $\sin\theta_{\text{out}}$ vs. $\sin\theta_{\text{in}}$. Have Kaleidagraph calculate the best fit line and the uncertainty of the slope and intercept of the best fit line.

Observe total internal reflection

1. As in the previous part, make sure that the flat surface is at center of the circular protractor.

2. Rotate the protractor and observe the reflection inside the Lucite block (look from top down at the light trace inside the block. You may need to turn off the room lights to see it clearly). Hold your hand perpendicular to the flat side of the Lucite block and rotate the block until you see the laser light on your hand (you should see the laser point on your hand when you are under the critical angle).

3. Now, rotate the block until the refracted laser light that you see on your hand is along the flat surface of the block (if you rotate it further, the light should disappear from your hand). When the refracted laser light ray falls exactly on (parallel to) the flat surface, you are at the critical angle. Record your measurement of the angle and an estimate of the uncertainty of this measurement in your spreadsheet.

4. Obtain a piece of optical fiber. Shine the laser beam at one of the optical fiber and observe the results. Do not over-bend the optical fiber, as it is fragile and can easily break.

5.8   Questions

1. From your graph, what is the index of refraction of Lucite and its uncertainty? Compare Eq. 5.1 to the equation of a straight line with a y-intercept of zero: $\sin\theta_{\text{out}}$ plays the role of y, and $\sin\theta_{\text{in}}$ plays the role of x.

2. Is your measured value for the index of refraction of Lucite in consistent with the accepted value of 1.55? Justify your response. If it was not consistent, suggest a possible reason for the apparent discrepancy.

3. You should have noticed that the light spot on the screen was larger when it passed through the semi cylindrical block than it was when the block was not in the laser light's path. Suggest a possible explanation for this observation.

4. Using the best fit line from your graph, calculate θ_C.

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5. Calculate the theoretical value of θ_C for a beam of light incident from Lucite $(n_1 = 1.55)$ to air $(n_2 = 1.00)$. Enter the value on your spread sheet and show your calculation below.

6. Discuss the consistency of the critical angle you measured in the third part of the experiment with the theoretical value you calculated in Question 5.

7. When you shined the laser light into one end of the optical fiber, did the light entering the optical fiber only exit through the other end of the optical fiber cable? Why or why not?

8. Give an example of an application of total internal reflection from medical or some other technology.

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