

## Geometrical Optics

The light source for this experiment is a low-power helium-neon laser with a wavelength of 632.8 nm. **Never look directly at a laser beam nor permit anyone else to do so!** Exposure to the direct or reflected beam for more than a few seconds will cause serious eye damage. Do not pick up the lasers and shine them around the room. If these simple precautions are taken then there will be no risk associated with the lasers as they are of relatively low power. Special note: if you have long hair, bringing something to keep your hair out of the laser beam is a good idea.

In this experiment you will be measuring the index of refraction. This is a number  $n \geq 1$  which represents the ratio  $c/v$ , where  $v$  is the speed of light in the medium and  $c$  is the speed of light in vacuum. For the measurements you make, you should find values of  $n$  between 1.4 and 1.6. Your measurements should allow you to determine  $n$  within 1-3%.

### Theory

The two basic principles of geometrical optics are the law of reflection and the law of refraction (Snell's Law). The law of reflection states that the angle of incidence is equal to the angle of reflection, both angles being measured from the normal to the surface, and that the incident ray, the normal and reflected ray are coplanar.

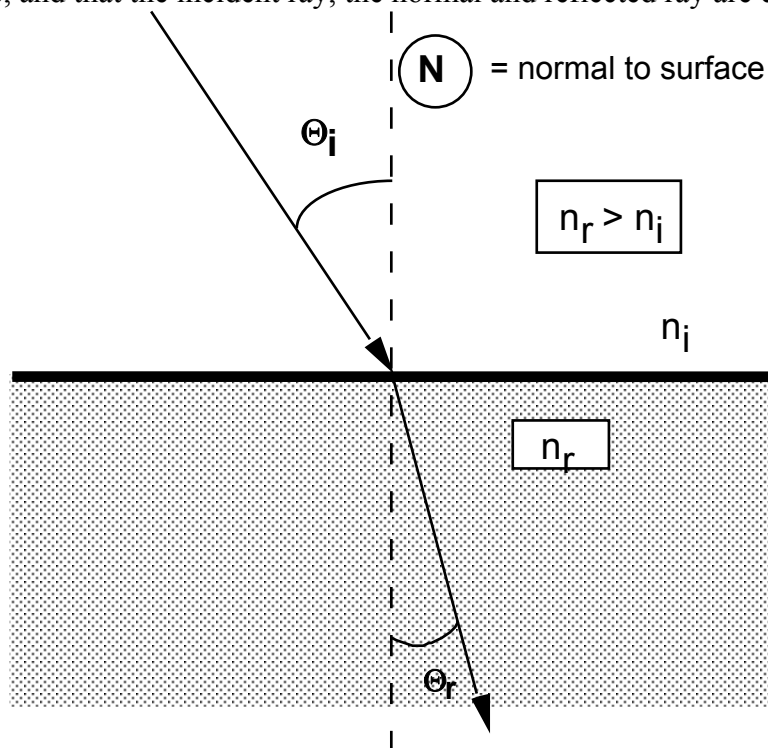


Fig. 1: Refraction at an interface between dissimilar media

Snell's law states that the incident ray, the refracted ray and the surface normal are coplanar and that:

$$n_i \sin \theta_i = n_r \sin \theta_r \quad (1)$$

where  $n_i$  and  $n_r$  are the indices of refraction of the two media involved. The medium with the larger index of refraction is said to be optically denser than the one with the smaller index. If the ray goes from the optically less dense to the optically more dense medium, then it is refracted toward the normal. If the ray enters from the optically more dense medium, it is refracted away from the normal. In that case, the maximum possible angle of refraction is  $90^\circ$  (along the interface) and the corresponding angle of incidence is then (from Eq. 1):

$$\theta_i = \theta_c = \sin^{-1} \left( \frac{n_r}{n_i} \right) \quad (2)$$

which is called the critical angle. If the angle of incidence is larger than the critical angle, there cannot be a refracted ray and the beam is **totally internally reflected**.

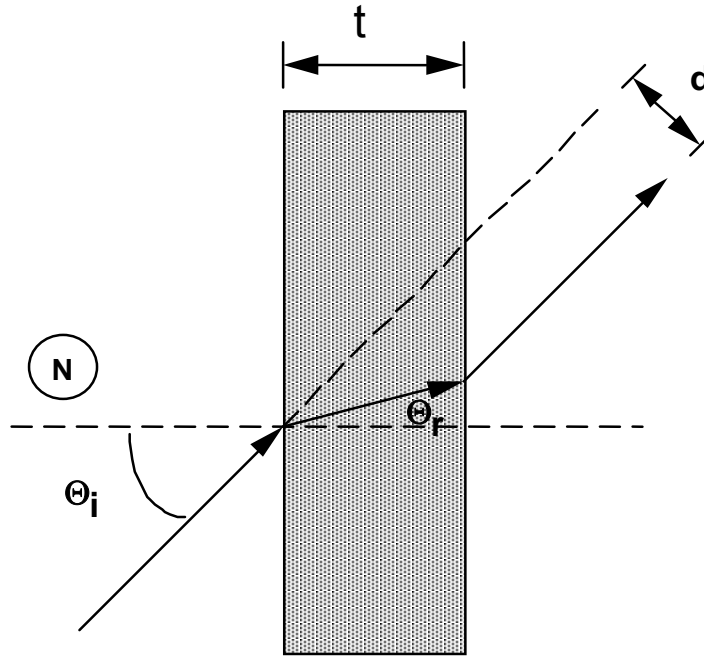


Fig. 2: Refraction through a slab.

The **optical micrometer**, a device for precisely displacing a light beam, is shown in figure 2 above. A light ray traversing a plate of material with parallel entrance and exit faces is displaced laterally without a change in direction. This displacement effect is very useful for laser surveying and laser control of instruments. With high-quality apparatus, displacements as small as one-tenth of one millimeter can be measured and controlled over sizable distances. It can be shown from Snell's law that the lateral displacement  $d$  of the beam is given by:

$$d = \frac{t}{\cos \theta_r} \sin(\theta_i - \theta_r) \quad (3)$$

where  $t$  is the thickness of the slab and  $\Theta_i$ ,  $\Theta_r$  are the angles of incidence and refraction of the *entering* beam. [The roles of these two angles are reversed for the exit beam].

**Extra Credit:** Derive Eq 3 and explain why  $n$  doesn't appear in it.

## Procedure

Be sure to *make sketches* of all your setups and indicate trajectories of rays.

1. Set up the optical table so that the laser beam is parallel to axis of the optical beam and also parallel to the surface of the table, 2 to 3 mm above it, and traverses the table directly above the zero degree median line of the protractor circle. Lock the table in place. Beam positions can always be easily located by interposing a file card into the path of the beam.
2. Look ahead through the procedure and decide on a good position for the protractor optical table and the moveable screen. Mount the semicircular lens on the protractor circle with the flat surface facing the laser with the pointer at  $0^\circ$ . Make sure that the beam is positioned over the center of the semicircular lens. Autocollimate the beam by rotating the optical table until the reflected beam bounces back into the opening on the laser face. You might not actually see this, but you can see when the reflected beam hits to the right or to the left of the opening and adjust accordingly. From now on you should only rotate the protractor. The protractor sits on the optical table, and allows you to change the orientation of the lenses.

Q1) Why is it important that the beam pass over the center of the lens?

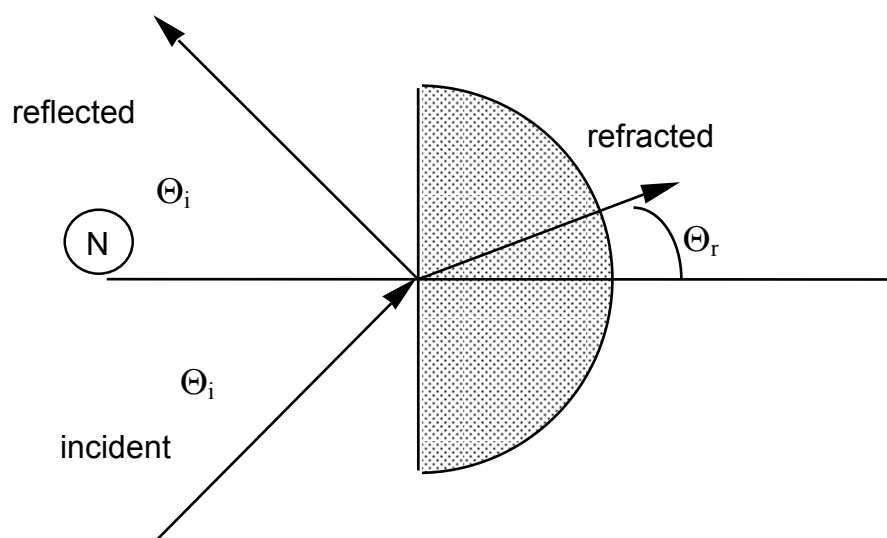


Fig. 3: Reflection and refraction from a semicircular lens.

3. Record the position of the refracted laser beam for a series of incident angles in  $10^\circ$  steps. Don't go past  $50^\circ$  or the optical table supporting the protractor may rotate; be sure this optical table isn't rotated between measurements. Note that the beam leaves the lens at right angles to the curved surface and is therefore not refracted on leaving. Qualitatively observe the intensities of the reflected and refracted beams as the angle of incidence is varied and note this in your lab book.
4. For each of your measurements separately, calculate the index of refraction of the plastic material from Snell's law, then average your calculated values to get the mean value and determine the standard deviation and the standard deviation of the mean. **You will need to have a good sketch** of your setup to relate the measured angles to those needed to apply Snell's Law. Take 1.0 as the value of  $n_{\text{air}}$ .

Q2) Extra Credit: Write out how you would estimate the uncertainty of the calculated index of refraction, given the uncertainty in angle and position.

5. Rotate the protractor by 180 degrees and so the curved surface is toward the laser. Observe the behavior of the beams reflected and refracted at the flat surface. Note that the entering beam is not refracted. Again observe the intensities qualitatively for angles of incidence smaller and larger than the critical angle. **Make a sketch** in your lab book explaining your criterion for defining when you are at the critical angle. Determine the critical angle, and from it calculate the index of refraction. Repeat this measurement of the index of refraction several times, then compute the mean value and the standard deviation for the mean of the index of refraction and compare it to your previous measurement (in step 4). **Extra Credit:** take and analyze refraction measurements like steps 3-4 in this geometry.

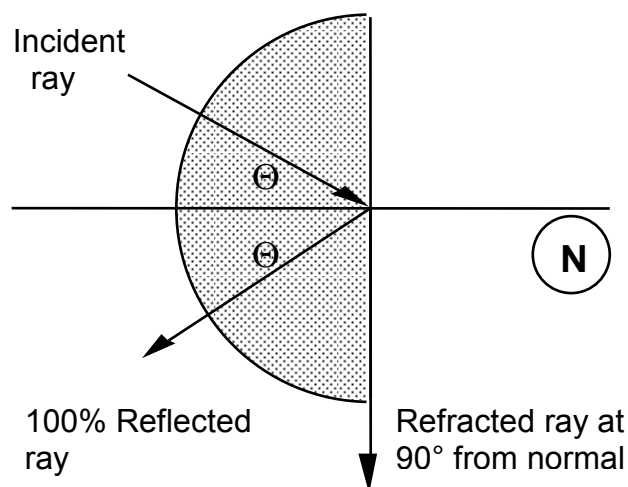


Fig. 4: Total internal reflection; the angles  $\theta$  depend on the material.

6. Mount the flat plate. For these measurements, which way should it be oriented? **Make a sketch** in your lab book. Autocollimate the beam. You should do this set of measurements with a smaller distance between the screen and the optical table, and again with a larger distance, having measured the distance  $L$  between your

near and far points of observation. For each set, record the lateral displacement  $d$  of the laser beam for a series of angles of incidence in  $10^\circ$  steps. Measure  $t$ , the thickness of your plate, with a caliper. If you don't know how to use the caliper scale, look in the reference guide. Estimate your measurement errors for  $d$  and  $t$ .

7. For each of your angles of incidence separately, “predict” the displacement  $d$  from Eq. 3, using the value for the index of refraction measured in part 4 above. Compare your calculations with the measured values of  $d$ .

**Extra Credit:** make this comparison taking into account the uncertainty of the measurements.

8. In practice, the laser beam may emerge not only displaced laterally, but also making some angle  $\Theta_{dev}$  with respect to the incident path. Referring to figure 5 below, use the equation (valid for small angles measured in radians, for which  $\tan\theta \approx \sin\theta \approx \theta$ )

$$\Theta_{dev} = \frac{d_{far} - d_{near}}{L} \quad (4)$$

to calculate the angle of deviation and its uncertainty, for each of your measurement pairs (near and far) from part 6. Note that the angle can be either positive or negative. You may also find it useful to calculate the mean and standard deviation. Discuss your findings.

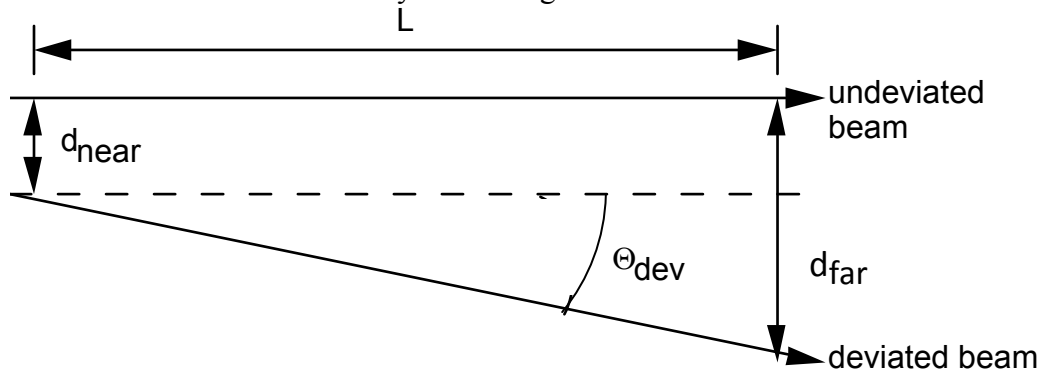


Fig. 5: Deviation of beam going through slab.

Q3) In your measurements, do the 0 degrees values agree with the position of the beam with no optical element in place? If not, what might this be due to?