

Fresnel Equations and Electromagnetic Boundary Conditions

Note: Prior to reading this write-up you should read the Background information on Fresnel's equations from the course webpage.

Goal:

- to test experimentally Fresnel equations for the case of a non-conducting, nonmagnetic transparent medium
- to measure the angle and polarization dependence of the reflection and transmission of light at the interface between air and an unknown transparent material.
- to obtain the index refraction, the critical angle and Brewster's angle for this material from fitting the intensities of the reflected and refracted beams as a function of the incident angle with Fresnel's equations.

Theory: Read the supplementary material on the course webpage and Ref. 1(a copy is in the reading binder of this experiment).

Apparatus: Laser diode, silicon detector, angle table, semicircular glass or plastic sample.

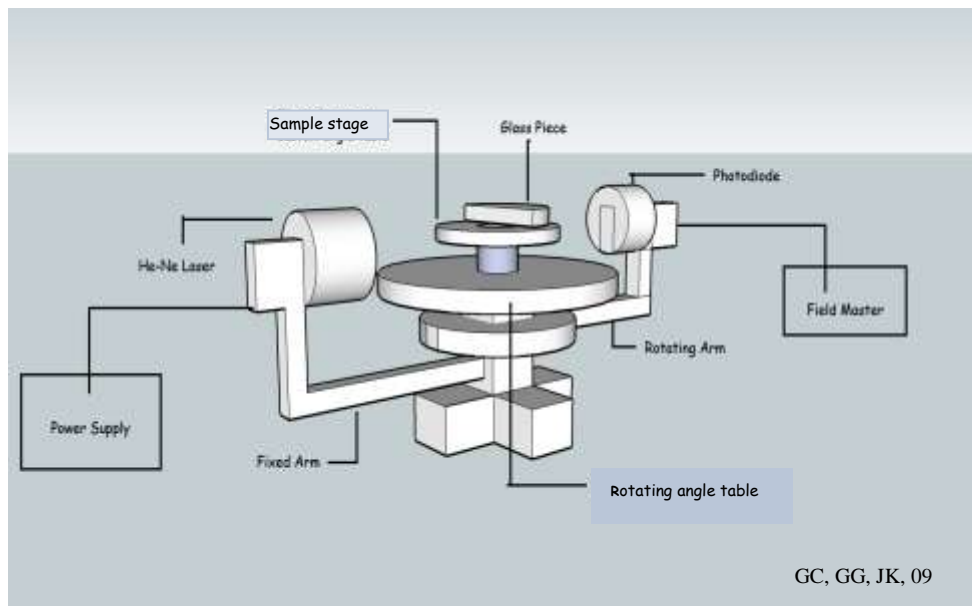


Figure 1. Schematic of measurement setup.

The angle table and detector position are controlled by three set of screws. Each set consists of a coarse lock-screw and a fine adjustment screw. The top set controls the table height and horizontal tilt. To adjust the height release the coarse lock-screw and lift up or push down the stage to desired height and tighten the lock screw. The tilt is adjusted by the three small vertical screws supporting the table. It is important to adjust the tilt so that the laser beam is parallel to the table (devise a way to achieve the alignment) . The middle set controls the position of the detector arm. Release the lock-screw and retighten it after swinging the detector to the desired position. Use the fine controls to maximize the signal. The bottom set controls the table. Release lock-screw to align table to the desired position . You can read the relative angle between table and detector position with high precision through the magnifying glass cover on the viewing windows. Devise a way to keep track of this angle in a consistent manner throughout the experiment. To change the angle release the set screws, turn to desired position and *gently* retighten setscrews.

Suggestion. One way to take data is to loosen the detector arm locking screw and rotate it slightly from its previous position, without attempting to set at a precise angle. (Grip the arm, not the detector. Be careful not to move the laser.) Then rotate the sample table until the reflected laser beam is visible on the photodetector, lock the detector arm and adjust its angle for maximum meter voltage with the fine control screw. Read the coarse angle and vernier. For detector angle readings R to the right of zero, angle i is $(180-R)/2$; to the left, $i = (R-180)/2$. (Check that these make sense.) Record read angles R and let the fitting program (e.g., origin) calculate later the corresponding values of i . This procedure will result in some systematic error due to initial inaccurate positioning of the sample . This systematic error can be reduced when you compare your experimental results with Fresnel equations.

You may find that other methods may work equally well or better for a particular measurement.

Procedure:

- **Be careful not to look into the laser beam.**
- **Never exceed 3 volts in the laser supply.**

1. **Calibration.** Turn on the laser diode power supply ($< 3V$) and the silicon detector. Adjust the wavelength registered by the detector to 670 nm – this is the wavelength of the red light emitted by the laser. For calibration purposes, observe and record the laser beam intensity when the beam

is directed to the silicon detector (without being reflected or refracted) separately for perpendicular and parallel polarization. (The direction of polarization of the laser light with respect to the sample's plane is shown on top of its housing; to change the direction of polarization, release the screws that fix the housing, rotate it by 90° , and tighten the screws again). Adjust the relative position of beam and detector for maximum signal. Record the position dependence. You will need to do this at every step as the alignment of the detector and its housing may not be perfect.

- Initial observation.** Place the semicircular sample on the angle table. The sample must be centered on its turntable to avoid angle changes on exit. See schematics in figure 2. To familiarize yourself with the setup start by detecting the beam on a piece of paper wrapped around the table. This will allow you to see the positions of both reflected and transmitted beams. Observe what happens as you change the incident angle. You should be able to see Brewster's angle and the critical angle. Record the values. For Brewster's angle measure the angle between the reflected and refracted beams. How does it compare to the expected value. Repeat for both sample configurations and for both polarizations. Record your result and include in your report.

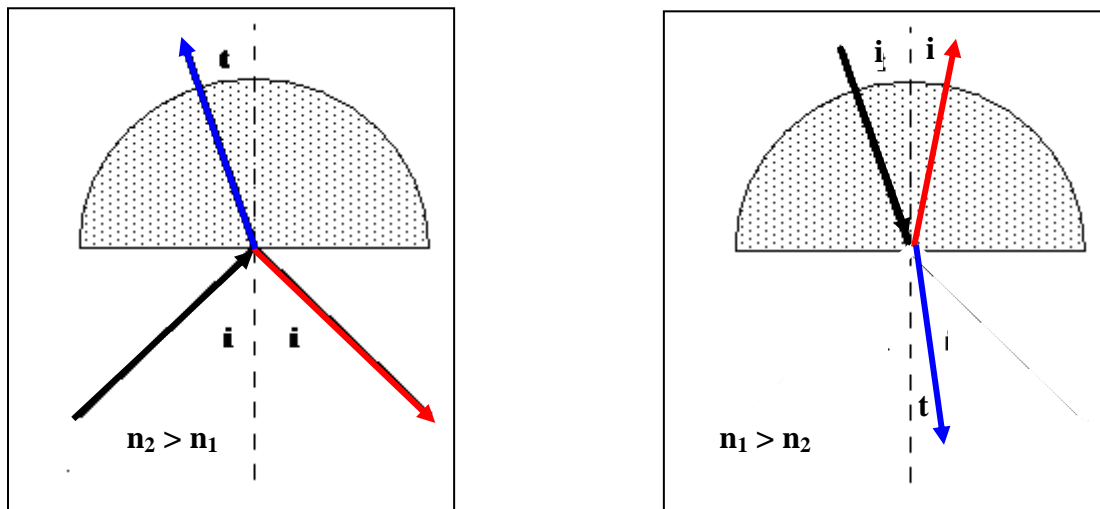


Figure 2. Incoming reflected and transmitted beams for the two experimental configurations.

- Snell's Law.** Using the diode detector, measure the angle of the incident beam and the refracted beam for both the air to glass and glass to air interface, as depicted in Figure 2. Record the angle of refraction t as a function of the incident angle i . Plot $\sin(t)$ versus $\sin(i)$ and obtain

$(n_{\text{glass}}/n_{\text{air}})$ from the slope of a linear fit. Do these measurements for both the semicircular glass and semicircular plastic sample.

4. Fresnel equations for air/dielectric interface ($n_2 > n_1$).

In this part you will measure the reflected angle (same as incident angle), the refracted angle, and the corresponding intensities of the reflected and transmitted beams for both parallel and perpendicular polarization. These measurements will be done for the air to glass interface (depicted on the left in Figure 2) for both the semicircular glass and plastic sample. Repeat this measurement for 10-15 values of \mathbf{i} , focusing on points that are in regions of interest, such as near Brewster's angle.

For transmission measurements make sure the beam exits normal to the second interface (semicircular geometry with initial incidence at the center of the flat side of the semicircular sample). Otherwise the intensity on emergence into air is reduced by any reflection at the second interface. Observe and record I_0 (the laser beam intensity at zero degrees before sample placement). Place the semicircular sample on the holder so that the flat side of the sample faces the incident beam and the beam hits the center of the flat side. Measure the angle and intensity of the reflected beam I_R and the transmitted beam I_T . Do this for both the glass and plastic sample and both parallel and perpendicular polarization. For parallel incident polarization, measure the Brewster's angle. Make sure to have enough data around the angle because reflectance will be low. At these low reflection intensities direct observation of the beam may be more difficult with the linear meter than with the non-linear eye. A fit of the data both above and below the Brewster's angle may allow you to determine it more easily than direct observation. For the analysis, compare and record Brewster's angle from your best fit and compare to the result obtained in part 2.

5. Total internal reflection. Fresnel equations for dielectric/air interface: ($n_1 > n_2$)

Repeat the measurement for section 4 for the incident wave propagating through the denser medium (glass), again for both directions of polarization and for both reflected and transmitted light. This is the glass to air interface, depicted on the right in Figure 2. In this geometry, the systematic error due to multiple reflections will be larger. Make corresponding corrections on the basis of your estimates of losses for the normal incidence. Pay special

attention to the angle of the total internal reflection (critical angle). Does it depend on polarization?

Be sure that the incident beam enters the sample radially. This way the beam will not refract due to the first (air to glass) interface and you can measure the angle corresponding to the second (glass to air) interface, which we are interested in. For parallel incident polarization observe quantitatively the transmitted and the reflected beam which can be seen inside the sample, as the incidence angle is varied. Note the occurrence of Brewster's angle and of a (larger) angle of critical reflection at the second surface. Record these angles.

Take measurements of the incident angle, refracted angle, and their corresponding power for both directions of polarization, just like you did in part 4. In this geometry, the systematic error due to the multiple reflections will be larger. Make corresponding corrections on the basis of your estimate of losses for the normal incidence. Pay special attention to the angle of total internal reflection. Does it depend on polarization? Determine the internal Brewster's angle as well as possible, and the corresponding relative index of refraction.

For both the air to glass (part 4.) and glass to air (part 5.) interface, when measuring the intensity of the transmitted beam, you introduce some systematic error (why?). From comparison of the measured and calculated intensities of the transmitted beam ($T=1-R$, where T and R are the normalized intensities of the transmitted and reflected beams), estimate the losses when the beam passes through the air to glass interface at normal incidence. Do the same for the glass to air interface. Are the transmitted beam intensity losses the same for the air to glass and glass to air interfaces?

Report.

- Discuss the physics of Fresnel's equations and how they are verified by your experiment. Define Brewster's angle and the angle of total internal reflection and how they are determined in this experiment.
- Explain the mechanism of suppression of the (P polarized) reflected wave close to Brewster's angle on the basis of molecular optics (reradiation of the light waves by induced atomic or molecular dipoles).
- Briefly describe the measurement procedure.

- Include the plot obtained in part 3 of $\sin(t)$ versus $\sin(i)$ together with the mean square linear fit from which you determined the index of refraction and error.
- Plot intensities of the reflected and refracted beams as a function of the incident angle for both parallel and normal polarization for both experimental geometries. Fit the data with Fresnel's equations. From your fit, make a conclusion on the systematic error caused by inaccuracy of the initial alignment of the sample. If necessary, make corresponding corrections to the incident angle, and replot the dependences. Mark the positions of Brewster's angle and the angle total internal reflection.
- Show a zoom into the data around the Brewster angle and mark its location.
- Find the index of refraction n for the sample from your fit and, separately, from the Brewster's angle and the angle of total internal reflection. Compare the results for n obtained by different methods, (including part 3). What are your conclusions.
- Explain why the incident and refracted beams obey Snell's law regardless of their polarization. (What properties of the electromagnetic waves are used in the derivation of Snell's law? Is it important that the light waves are transverse?).

References:

1. P. Lorrain, D. P. Corson, and F. Lorrain, *Electromagnetic Fields and Waves*. 3rd ed. W.H.Freeman and Co., New York 1988.
2. D. J. Griffiths, *Introduction to Electrodynamics*, 3rd ed., Prentice Hall, Upper Saddle River 1999.
3. M. Dekker *et al.*, Quantitative investigation of Fresnel reflection in the electromagnetism laboratory. *Am. J. Phys.* **67** (1999) 606.
4. For semiconductor lasers and light-emitting diodes, see *Handbook of Optics*, vol.1, McGraw-Hill, New York 1996 (available in the Physics Labriry)