

EXPERIMENT 8

PFUND REFRACTION

A narrow beam of light passes through the face of a glass plate, then undergoes a diffuse reflection from the rear surface of the plate. The diffused light travels back toward the face. Part of this light passes through the face and part undergoes total internal reflection and reflects back to illuminate the rear surface. When viewed from the front, the result is a dark circle with a bright spot in the center. The circle is surrounded by a bright ring. If the thickness of the glass plate and the diameter of the dark circle are known, then the index of refraction of the glass can be found.

THEORY, Part I

When a ray of light travels across a boundary from a higher index medium to a lower index medium, the light ray is bent away from the normal due to differences in the speed at which light travels in the two media. As the angle between the normal and the incident ray increases, the angle between the normal and the refracted ray also increases until at a particular angle the refracted ray is parallel to the boundary. (Refer to Figure 1.) In this case, the angle of incidence is called the critical angle, θ_c , and all the light incident at this angle or greater is reflected back into the first medium.

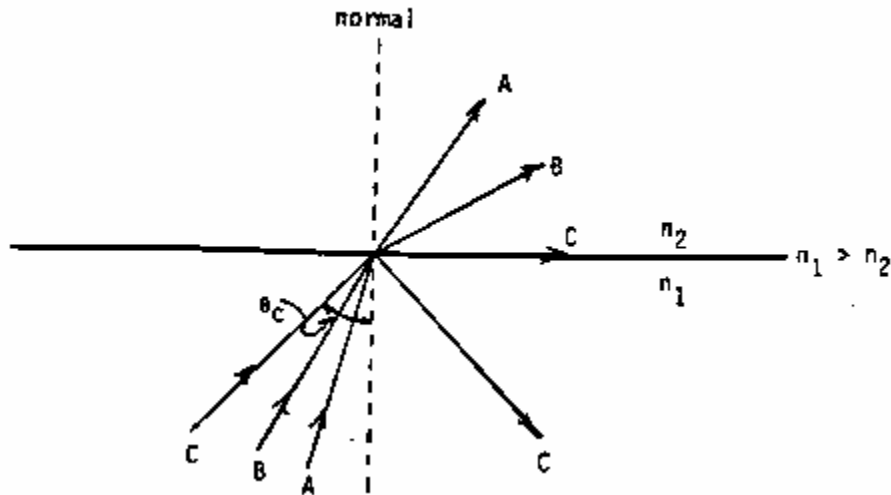


Figure 1. Light rays striking the boundary at various angles.

Ray C undergoes total internal reflection at the critical angle, θ_c .

When Snell's Law is applied to this situation, the result is

$$n_1 = \frac{n_2}{\sin \theta_c}. \quad (1)$$

Equation (1) gives the index of refraction of medium 1 in terms of the index of refraction of medium 2 and the critical angle.

In this experiment, a narrow beam of light from a laser is shined through the face of a glass plate and on the rear surface of the plate. The rear surface is coated with white paint that reflects and scatters the light back toward the face of the plate. (Refer to Figure 2.) Some of the light incident on the face passes back through the face. However, the light that strikes the face at the critical angle (ray C) or greater is reflected back toward the painted surface and illuminates that portion beyond point P. The overall effect creates a dark circle surrounded by a ring of light.

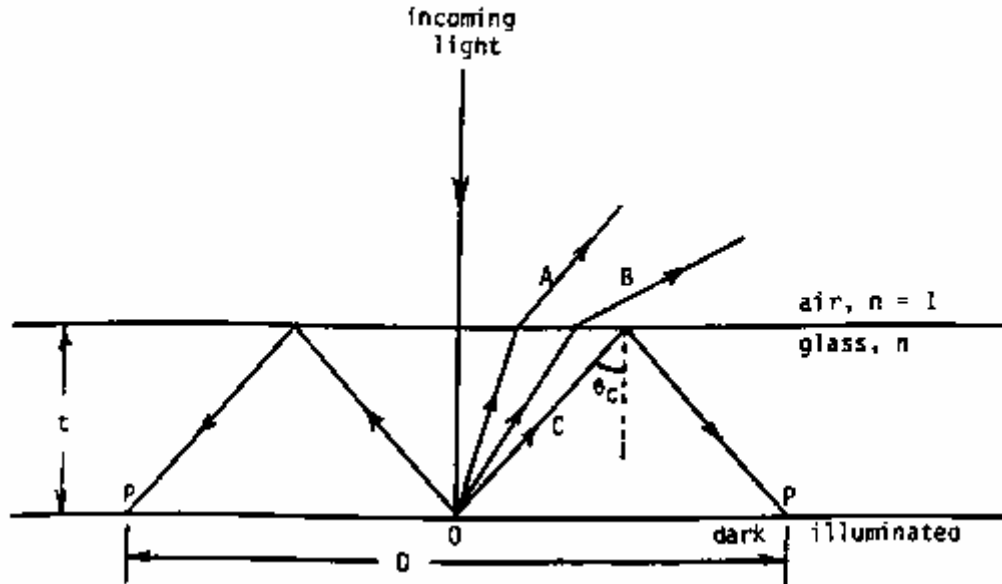


Figure 2. Light incident at point O scatters and produces a dark circle and an illuminated ring.

Using Snell's Law and trigonometry, the index of refraction of the glass plate can be found as

$$\eta = \frac{\sqrt{D^2 + 16t^2}}{D}. \quad (2)$$

THEORY, Part 2

If a liquid of index of refraction n_1 is placed on top of the glass plate, then total internal reflection occurs at both the glass-liquid boundary and the liquid-air boundary. The rays that undergo total internal reflection at the boundaries are shown in Figure 3. In this situation a dark circle surrounded a bright ring fading into a dark ring at a larger radius appears on the rear surface. The dark circle has a radius OP which corresponds to the internal reflection at the liquid-air boundary. The dark ring has a radius OP and corresponds to the internal reflection at the glass-liquid boundary. This ring is the one of interest.

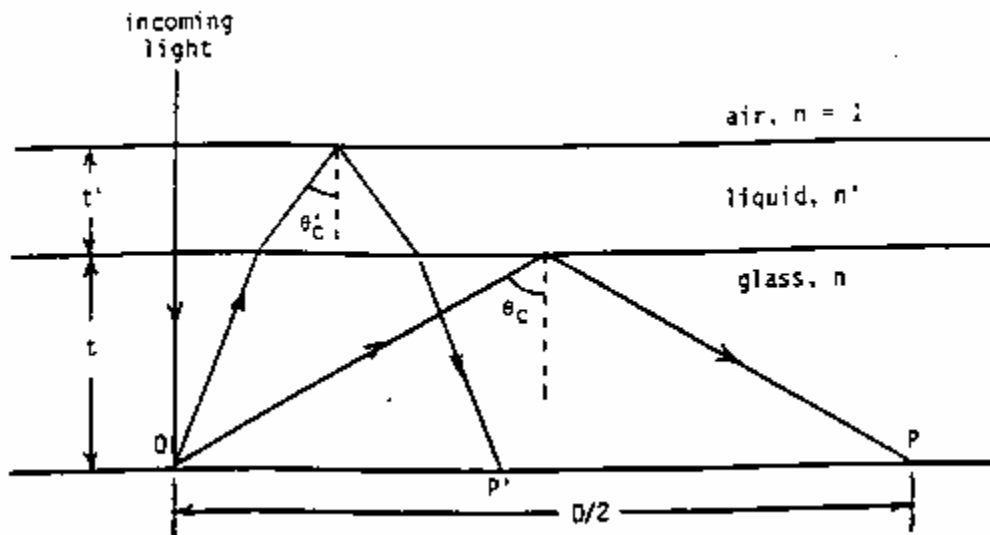


Figure 3. Light incident at point O is scattered and produces internal reflections at the glass-liquid and liquid-air boundaries.

Using Snell's Law, trigonometry, and the information from Figure 3, the index of refraction of the liquid, n' , can be found if n , t , and D are known. The expression is

APPARATUS

- | | | | |
|---|---------------------------------|---|-------------|
| o | glass plate with ruler attached | o | ring stand |
| o | right angle clamp | o | micrometer |
| o | rod to support laser | o | He-Ne laser |

PROCEDURE, Part I

- Measure the thickness of the glass plate, t , and its uncertainty, δt . Be sure the thickness is determined at a spot on the plate without paint.
- Position the glass plate underneath the laser so that the light can shine down on it. Ensure that the light will not reflect into anyone's eye.

CAUTION: Be sure the laser is never pointed toward anybody and that any reflections of the laser beam will not reflect into anyone's face. The laser light is a highly intense, collimated beam that can cause damage to the retina.

Turn on the laser. Adjust the position of the spot until it is adjacent to the ruler.

Measure the diameter, D , of the dark circle and its uncertainty, δD .

- c) Repeat the measurements of the diameter two more times at different positions along the ruler.

PROCEDURE, Part 2

- a) Place a few drops of water on top of the glass plate and smear them around with your finger.
- b) Shine the laser down on the plate and notice that a dark circle surrounded by a bright ring fading into a dark ring appears. The dark ring is faint and difficult to see. The bright ring is produced by internal reflections at the liquid-air boundary, and the outer dark ring is produced by internal reflections at the glass-liquid boundary. Position the glass plate so that the diameter of the outer dark ring can be measured. Record the diameter, D , and its uncertainty, δD .
- c) Repeat two more times at different positions along the ruler.
- d) Turn off the laser.

ANALYSIS, Part 1

The maximum and minimum values of the index of refraction of the glass plate are given by the expressions

$$\eta_{\max} = \frac{\sqrt{(D + \delta D)^2 + 1\delta(t + \delta t)^2}}{D - \delta D}, \quad (4)$$

and

$$\eta_{\min} = \frac{\sqrt{(D - \delta D)^2 + 1\delta(t - \delta t)^2}}{D + \delta D}. \quad (5)$$

The best value for the index of refraction of the glass plate is

$$\eta = \frac{1}{2}(\eta_{\max} + \eta_{\min}), \quad (6)$$

and the uncertainty in the value of the index of refraction is

$$\delta\eta = \frac{1}{2}(\eta_{\max} - \eta_{\min}). \quad (7)$$

For each of the three trials, calculate the best value of the index of refraction of the glass plate and the corresponding uncertainty. Report in a table, each of these values together with the best known value of the index of refraction for the glass plate of 1.50. Also graph these values on a one-dimensional graph.

ANALYSIS, Part 2

The maximum and minimum values of the index of refraction of the liquid are

$$\eta'_{\max} = \frac{\eta(D + \delta D)}{\sqrt{(D - \delta D)^2 + 1\delta(t - \delta t)}}, \quad (8)$$

and

$$\eta'_{\min} = \frac{\eta(D - \delta D)}{\sqrt{(D + \delta D)^2 + 1\delta(t + \delta t)}}. \quad (9)$$

The best value of the index of refraction of the liquid is

$$\eta' = \frac{1}{2}(\eta'_{\max} + \eta'_{\min}), \quad (10)$$

and the uncertainty is

$$\delta\eta' = \frac{1}{2}(\eta'_{\max} - \eta'_{\min}). \quad (11)$$

For the three trials, use the value of $n = 1.50$ for the index of refraction of the glass plate and calculate the best values for the index of refraction of the liquid and the corresponding uncertainties. Report these values, together with the accepted value of the index of refraction of the liquid in a table. Also graph these values on a one-dimensional graph.

QUESTIONS

1. Prove that total internal reflection can only occur when light travels from a medium of higher index of refraction into a medium of lower index.
2. What does a fish in a lake see when it looks up toward the smooth surface of a lake?
3. Start with Snell's Law and the information in Figure 2, and derive (2).
4. Derive (3).
5. Should the value for the index of refraction of the glass plate be the same for a white light source and for the laser? Explain.

6. If the water on top of the glass plate is replaced with glycerin, what happens to the pattern seen on the glass plate? Explain.