Prisms, gratings, and the spectrum of an incandescent bulb

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(Dated: November 17, 2022)

I. INTRODUCTION

We observe the diffraction of a laser beam using a diffraction grating and measure the angles of diffraction to confirm the theoretical predictions. Using a prism, incandescent bulb, and diffraction grating, we observe the wavelength of the light produced. Finally, we estimate the wavelength from our measured spectral intensity of the radiation from the incandescent bulb.

II. THEORETICAL BACKGROUND

Electromagnetic waves in the visible spectrum, 400 nanometers to 700 nanometers, are approximated as rays in geometrical optics since their wavelengths are small enough that this is adequate for certain behavioral observations. [1] [2]

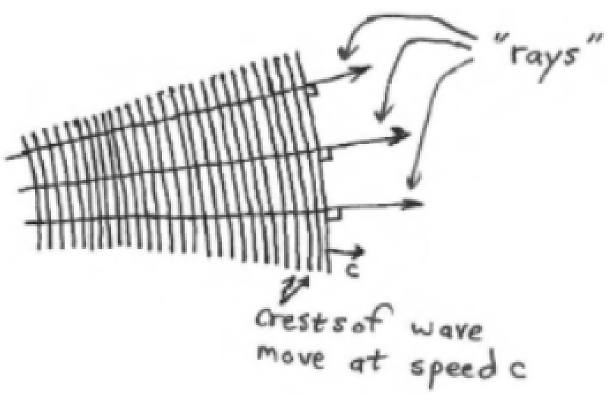

FIG. 1. Wave approximated by rays [1]

A. Dielectrics

Electrons in materials that are nearly all strongly bound to an atom are called dielectrics. A transparent dielectric is a material that is homogeneous and all electrons within behave as if harmonically bound with a resonance frequency higher than the frequency of visible light. [1]

The oscillating electric field of the light that interacts with a dielectric material exerts an oscillating force on the electrons in the material, causing them to behave as driven oscillators. The electron's are driven far below resonance since their resonant frequency is might higher than the frequency of the visible light. [3] The dielectrics are transparent due to the electrons oscillating in phase with the driving force and not absorbing any of its energy. [4]

The oscillating electron radiates a spherical electromagnetic wave with the same frequency of the incident light. This alters the wavelength of the light inside the dielectric since the total electric field is a superposition of the fields from the spherical waves from the electrons and the field of the incident light wave. [4]

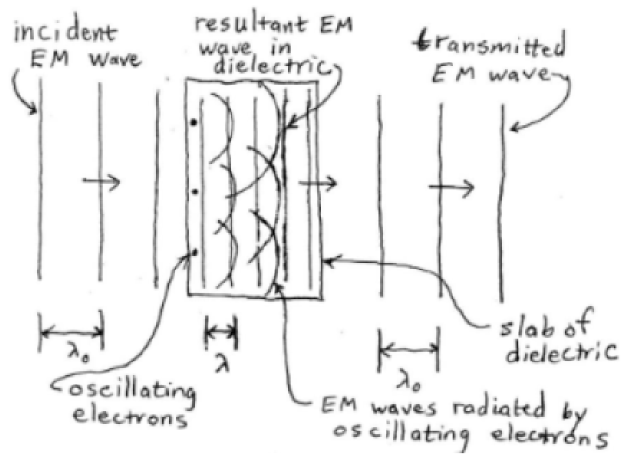

FIG. 2. The effect on wavelength inside a dielectric [1]

The resulting change in the wavelength inside the dielectric and the bending of the light ray is referred to as refraction. The index of refraction is given by the ratio of the wavelength outside the dielectric to the wavelength inside the dielectric, shown in equation 1.

$$n = \frac{\lambda_0}{\lambda} \tag{1}$$

Fresnel reflection describes the partial reflection of a light beam when encountering a discontinuity of refractive index. In addition, the direction of the ray is changed at this discontinuity. The refracted is given by

$$n1sin\theta_1 = n2sin\theta_2, \tag{2}$$

known as Snell's law of refraction. [1]

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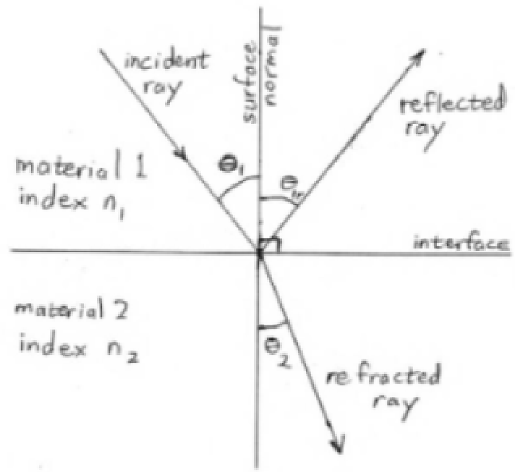

FIG. 3. Behavior of light at refractive index discontinuity [1]

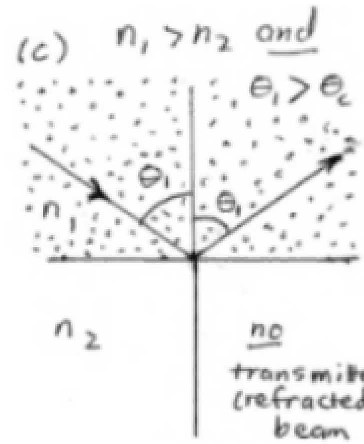

FIG. 5. Total internal reflection [1]

B. Speed of wave in dielectric

The speed of a wave in a dielectric material is given by

$$v = \frac{c}{n(\lambda)}. \tag{3}$$

In general, n increases as a function of wavelength, so the angles of refraction in Snell's law are wavelength dependent. [CITE]

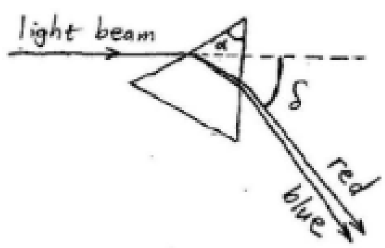

FIG. 4. Wavelength dependence of the refractive index of a dielectric material [1]

C. Total Internal Reflection

Total internal reflection occurs when n1 > n2 and the angle of incidence reaches the critical angle θ_c above which there is no refracted light ray. [1]

III. EXPERIMENTAL PROCEDURE

A. Setup

We used a double slotted wooden block with two pieces of foam in the slots to hold our laser pen. We began by taking out our double slotted wooden block and marking on the pieces of foam approximately where we needed to make cuts in order to fit the foam into the slots of our blocks. After making these marks, we used a craft knife to carefully cut the foam.

Next, we held our laser pen to the foam and again roughly marked where we need to make cuts in order to create a hole in each piece of foam that was just large enough to hold the laser pen. This hole needed to be cut tightly in order to depress the button which caused the pen to emit the laser beam.

After putting the laser pen and holder together, we then used a rubber band to hold another piece of foam to two different wooden blocks, in order to create a platform in the same plane as the laser beam. Finally, we used our remaining wooden blocks and foam to create "boards" for measuring our emitted beams as well as preventing the beams from leaving our experimental area.

B. Refraction Through Plexiglass

For the first part of the experiment, we measured the refraction through plexiglass. We began by placing our acrylic block on our platform so that one of its clear faces was perpendicular to the laser beam. Before turning our laser on, we placed a foam board behind the platform and behind our laser in order to contain the transmitted beam to our work area.

After turning on our laser (by pushing the laser pen forward so the button was depressed by the hole in the foam), we observed the light rays' pattern as we moved the plexiglass block.

In order to determine the index of refraction n of the plexiglass, we reoriented our block so that one of its clear faces was perpendicular to the laser beam and measured our block thickness D, the incident angle of the beam on the block, and ray separation using a ruler and protractor.

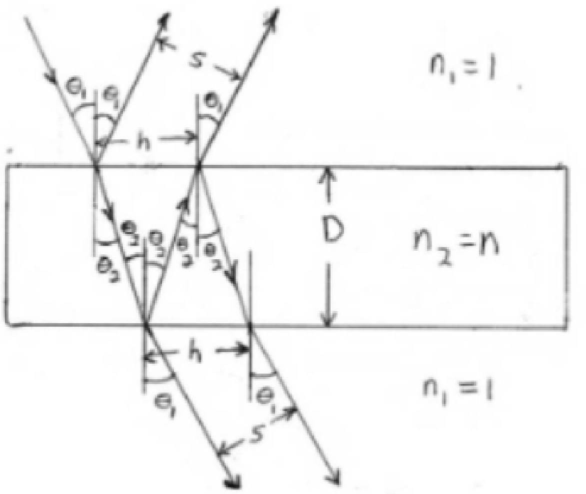

FIG. 6. Diagram of setup to measure refraction index of plexiglass [1]

C. Total Internal Reflection Using Porro Prisms

For the next section of our experiment, we turned off our laser and removed the plexiglass block, and then placed a Porro prism, a 90-45-45 degree prism, on our platform. We began by turning our laser on and directing the beam into the upper half of the long face of our prism and observing what happened to the beam.

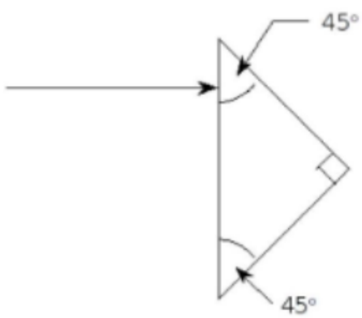

FIG. 7. Incident light on Porro prism [1]

Next, we turned our laser off and held the prism such that the 90 degree corner was opposite of our eye, and looked into the prism at the same corner we previously shone our laser into. We then tilted our prism slightly side to side and observed what happened, first with the apex of the prism vertical and then horizontal.

1. *Critical Angle Measurement of Porro Prism*

After placing our prism back on our platform and turning on our laser, we oriented our prism such that the angle of incidence was normal to the face of our prism. We then determined theta two using geometry and our given values for the index of refraction of our prism. We observed the critical angle increasing the incident angle theta one (by rotating our prism on our platform) until the transmitted beam nearly disappeared.

Next, we reoriented the prism so that the beam entered normally to the prism face at the top half of the prism as shown in figure 6. We observed whether the beam was reflected from or transmitted through the angled surface.

After turning the laser off, we placed a second Porro prism against the first as in figure 7. We turned the laser beam back on so that the beam entered the first prism as before. We again recorded how the beam behaved.

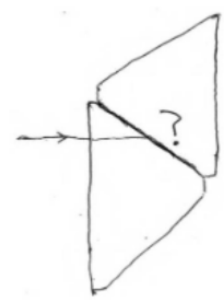

FIG. 8. Configuration of two Porro prisms [1]

Finally, we used a pipette to drop water between the two prism faces that were in contact and again observed the beams behavior.

IV. DATA

A. Refraction through Plexiglass

1. *Rays Incident on Plexiglass Block*

We observed that light rays were reflected and transmitted through the surface of the block. We noted that a pair of rays were emitted from the front (face of plexiglass closest to the laser) of the block, one of which was reflected from the front face, and the other reflected from the back. We also saw that some weaker beams were reflected twice.

When moving the block around, we noted that this changed the reflected and transmitted beam. When increasing the angle of incidence θ_1, the ray separation s increased as well.

2. Measurement 1: Plexiglass Index of Refraction

In order to make a calculation for the index of refraction of our plexiglass, we recorded the values listed in table I.

TABLE I. Beam Transmitted Through Plexiglass

D [cm]	s [cm]	θ_1 [Degrees]
3.8 ± 0.1	1.5 ± 0.1	13.35 ± 1.0

B. Total Internal Reflection Using Porro Prisms

When shining the laser beam into the prism as described, we observed that the beam was transmitted and reflected through the prism as shown in figure 8.

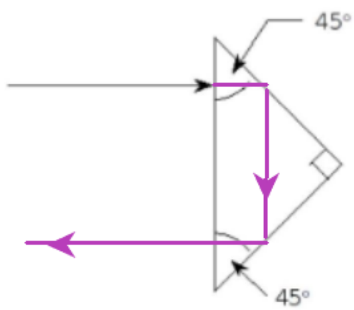

FIG. 9. Behavior of beam normally incident upon Porro prism as depicted

If two parallel rays were incident upon a Porro prism, the resulting rays would behave as depicted in figure 9.

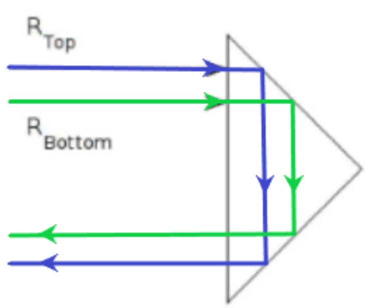

FIG. 10. Two parallel beams incident on a Porro prism

1. Observation of Porro Prism Behavior

With the Porro prism's apex oriented horizontally, when tilting the bottom of the prism closer to our face, we noticed that in the upper half of the prism we initially could see a reflection. As we tilted the prism more, the lower half switched to transmitting light and we could see what was on the other side of the prism, which in this case was our hand. In the lower half of the prism, we initially observed a distorted transmitted image and as we tilted, the transmitted image became more compressed horizontally. After tilting further, the lower half of the prism showed an upside down reflection.

With the Porro prism's apex oriented vertically, and the prism tilted up and down, both sides emitted clear reflections. When tilting the prism left, the left side switched from reflecting to transmitting, while the right side continued to reflect regardless of the degree of tilting.

2. Measurement 2: Critical Angle of Porro Prism

In order to determine the critical angle of the Porro prism, we measured the angle of incidence θ_1 and calculated θ_2 from the given indices of refraction. These values are listed in table II.

TABLE II. Measurements to determine critical angle of Porro prism

θ_1	θ_2 (N-BK7)	θ_2 (N-BAK4)
$10.84 \pm 1.5°$	$16.5 \pm 1.5°$	$17.1 \pm 1.5°$

C. Beam Behavior Inside Porro Prism

1. One Porro Prism

The beam of light directed normally into the prism as indicated was reflected from the angled surface.

2. Two Porro Prisms

When a second Porro prism was placed up against the first, the beam was still reflected from the first prism's angled surface.

3. Two Porro Prisms Connected by Water

After ensuring the water was between the two faces on the prism by capillary action, the beam was transmitted through the two prisms.

V. ANALYSIS

A. Refraction Through Plexiglass

1. Measurement 1: Index of Refraction of Plexiglass

We calculated our index of refraction n of the plexiglass to be 1.16 ± 0.4.

B. Total Internal Reflection Using Porro Prisms

1. Beam Behavior Inside Porro Prism

The beam behaved as depicted in figure 8 due to the change in the index of refraction as well as the reflecting angled surfaces and transmitting face.

The critical angles for N-BK7 and N-BAK4 optical glasses are given in table III. An optics company may choose the more expensive N-BAK4 glass to measure more precise values. Also, since the index of refraction increases with increasing frequency, this could also be a factor in their decision.

TABLE III. Critical Angle of Optical Glass

Optical Glass	λ [nm]	n	θ_c [Degrees]
N-BK7	650	1.514	59.5 ± 1.5
N-BAK4	650	1.566	57.5 ± 1.5

You could use these prisms to observe an object while preserving the orientation of the object.

2. Measurement 2: Critical Angle of Porro Prism

We measured a critical angle for our Porro prism of 59.5 ± 1.5 degrees.

Within our bounds of uncertainty, we cannot accurately determine which type of glass our prism is made from.

When the two Porro prisms are connected by capillary action of the water, they act as one block. The water eliminates the interruption between the indices of refraction which are present when the two prisms are only pressed against each other.

VI. CONCLUSION

Issues with the index of refraction of the plexiglass could have arisen since the surface we took measurements on was not perfectly flat. This was noticed when measuring the separation of the transmitted and reflected beams, s. One of the beams had an elevation above the other.

Measurements of the beams were taken by drawing lines along the beams, which not very precise or reliable and could be improved by more advanced means.

Another issue contributing to systematic error in this experiment was due to the approximation of the laser's beam as a two dimensional line and one dimensional point, depending on what was being measured, when the beam emitted is not a perfect point or line. This was approximated by taking measurements at the centers of the laser beam lines or points. There is also the issue of aberration from the emitted laser beam.

Additionally, as discussed in the theoretical background section, a ray is already an approximation of an electromagnetic wave, so this is a source of systematic error as well.

Another source of systemic error in this experiment is the correction for the speed of light in a vacuum. Our dielectrics were also not in a vacuum.

The accuracy of the lengths and angles calculated could be increased by using a measuring device which had a length scale more precise than the centimeter ruler we employed. Generally, the results could be more accurate if an increased number of measurements were taken, therefore reducing error. [5]

[1] D. Heinzen, Refraction of light, (2020).
[2] G. C. King, *Vibrations and Waves*, 1st ed. (Wiley, 2009).
[3] R. Fitzpatrick, *Oscillations and Waves: An Introduction*, 1st ed. (CRC Press, 2017).
[4] R. P. Feynman, *The Feynman Lectures on Physics*, Vol. 3 (Addison Wesley, 1971).
[5] P. Bevington and D. K. Robinson, *Data Reduction and Error Analysis for Physical Sciences*, 3rd ed., Vol. 2 (McGraw-Hill Education, 2002).
[6] R. P. Feynman, Phys. Rev. **94**, 262 (1954).