Experiment

VI   Polarized Light

I. Purpose

In this lab you will study some of the properties of linearly polarized light.

II. References (Course Textbooks)

Optics, by Eugene Hecht, 4th Edition

III. Equipment

Diode laser, < 1 mw, 670 nm	Laser beam blocker (at end of optical bench)
Laser beam blocker (near laser)	Magnifying glass (lens, 5cm focal length)
Quarter wave plate	Lens,50 cm focal length
Plane polarizer, simple, 2 each	Swinging arm assembly with angles scale
Swinging arm stabilizing rod	Optical bench, sliders and holders
Dielectric plate samples	Computer with Logger Pro software

Plane polarizer, calibrated, in rotating mount
Light sensor with mini-screen and 3-level sensitivity box
Baffle for light sensor (black electrical tape or black 35mm film can)

IV.   Pre-Lab Questions (due at the start of lab class)

1. (a) If the incident light is unpolarized, about what fraction of the light intensity gets through a plane polarizer?
   (b) How much unpolarized light is passed by a combination of the first polarizer and a second that has its polarization axis at 45^0 with respect to the first?

2. If two polarizers are aligned so that they are perpendicular, then no light will pass through. If you insert a third polarizer in between the first two with its polarization axis at 45^0 with respect to each of the others, what fraction of a beam of unpolarized light will get through all three? (Hint: it's not zero!).

3. Explain how the experiment described in Prelab question 2 above shows the difference between filters that only remove light and polarizers that change the state of polarization.

4. Explain what Brewster's angle is. Calculate Brewster's angle for glass with an index of refraction of n = 1.5.

V.   Introduction

Classically, light is a wave of oscillating electric and magnetic fields. For light that is propagating freely in space (in isotropic media), the electric and magnetic fields always point in directions that are perpendicular to each other, and to the direction the light is traveling. We say that light is a "transverse wave". By convention, the direction of polarization is a direction
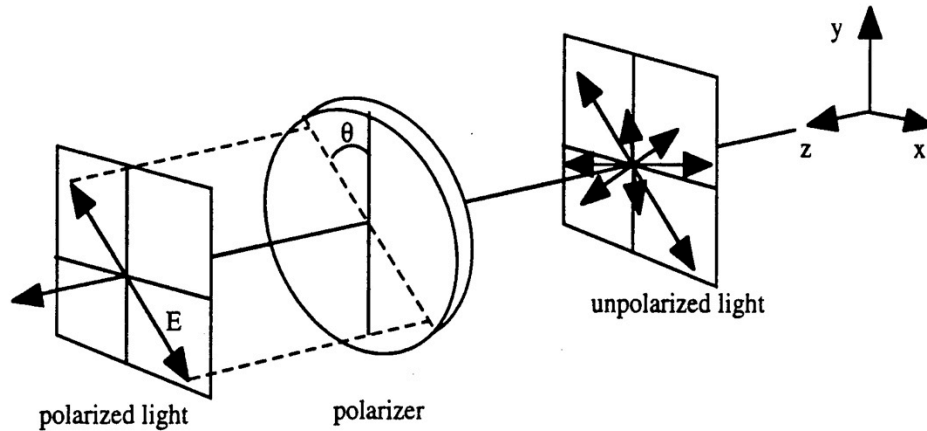
Fig. VI.1. *Unpolarized light propagating along the +z axis has electric field pointing randomly in the x-y plane. If the light passes through a polarizer that is oriented at angle θ with respect to the y axis, the light will have an electric field that is polarized at angle θ.*

parallel to the electric field, E, which is a vector.

In an unpolarized beam of light, such as that from an ordinary light bulb, the electric field points in random directions (of course all of these directions are always perpendicular to the direction in which the light is traveling). For linearly polarized light, the electric field points along one particular direction, called the "polarization direction". For example, suppose a light beam is propagating in the z-direction and is linearly polarized in the x-direction. In this case, the electric field is oscillating in the ±x direction.

If you have a source of unpolarized light, you can turn it into polarized light by passing it through a "polarizer". You have probably encountered polarizers before in sunglasses. The most common type of polarizer consists of strands of long chain polymeric molecules containing iodine atoms. These strands are aligned approximately parallel to one another and are highly conducting along the strands. As a result, the component of the vibrating electric field, E, which is parallel to the strand's direction is strongly absorbed and the component of E perpendicular to that direction is affected very little. The result is that after passing through a polarizer, the light is left with an E field predominantly oscillating along just one direction (see Figure VI.1).

For convenience we can define the "direction of the polarizer" or "the transmission direction or axis" as the direction perpendicular to the orientation of the strands; with this definition light passes freely if polarized in the direction of the polarizer. The intensity of light *I* is proportional to the square of the electric field vector, $|E|^2$. If light is partially polarized, the percentage of polarization is defined as

$$\text{percentage polarization} = \frac{I_{max} - I_{min}}{I_{max} + I_{min}} \times 100\%,$$

where I_{max} and I_{min} are the maximum and the minimum values, respectively, of the intensity observed when rotating a polarizer in a plane that is perpendicular to the direction of the light propagation. Note, unpolarized light shows no variation of intensity as the polarizer is rotated. However, you should also be aware that the intensity of light transmitted by the polarizer is only one-half of that of the original light intensity, because one component of the electric field has been eliminated. This points out an important principle: the E field can always be broken into two orthogonal components of equal magnitude.

Now suppose we have two plane polarizers whose directions of polarization are oriented
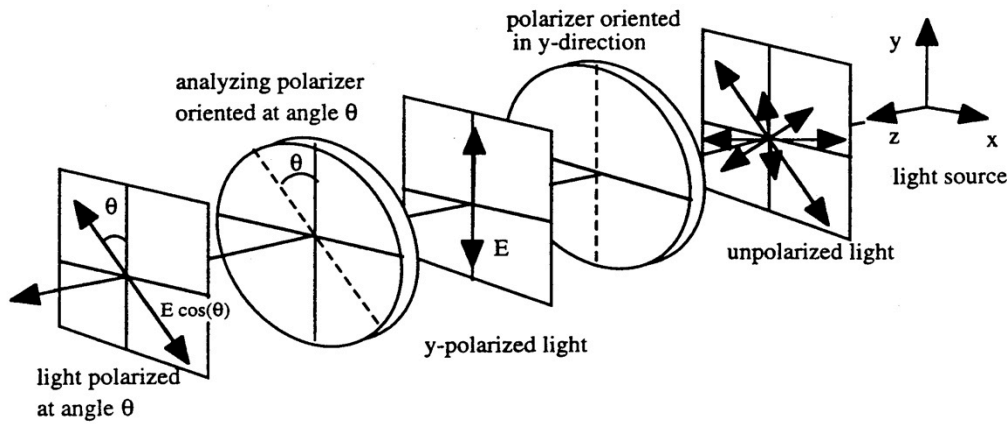
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Fig. VI.2. *Unpolarized light is polarized in the y-direction after passing through the first polarizer, and at an angle θ after passing through the second polarizer. If the light has an electric field strength E after passing through the first polarizer, then its field strength is E cosθ after passing through the second polarizer.*

at some angle θ with respect to one another as shown in Figure VI.2. The intensity of light transmitted by this combination of polarizers depends on the angle θ between the two directions of polarization. This dependence is known as the Law of Malus and is given by

$$I(\theta) = I(0)\cos^2\theta,$$

where I(0) is the transmitted intensity when the two polarizers are aligned (i.e., θ = 0).

Polarization by Reflection

When unpolarized light shines on a dielectric such as glass or plastic, the reflected light will be partially polarized. For light striking the surface of a dielectric at one special angle of incidence, called "Brewster's angle", ϕ_B, the reflected light will be completely polarized.

The electric field vector for light incident on a surface can be resolved into two parts, one part lying in the plane of incidence (the plane which is perpendicular to the surface of the dielectric and which contains the direction in which the light wave is propagating) and one perpendicular to the plane of incidence. Brewster discovered that at the angle ϕ_B the reflected wave is polarized perpendicular to the plane of incidence (i.e., out of the page in Fig. VI.3). He also found that ϕ_B depends on the index of refraction, n, of the dielectric according to the simple law:

$$\phi_B = \tan^{-1}n$$

In Figure VI.3 the plane of the paper is the plane of incidence. The heavy dots represent the component of the electric field vector pointing perpendicular to the plane of incidence, and
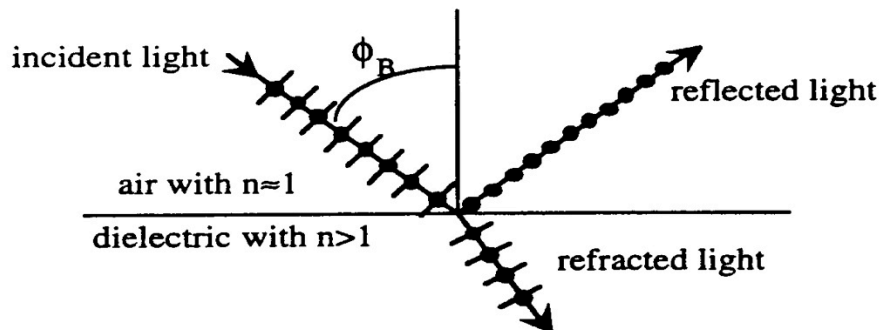

Figure VI.3. *Light incident at Brewster's angle on a dielectric with index of refraction n >1.*

the short lines represent the component of the electric field parallel to the plane of incidence (i.e., lying in the plane of the paper). The incident light is unpolarized and the reflected light is 100% polarized perpendicular to the plane of incidence.

Some common instances where reflected light is partially polarized are reflection off water and the glare off the hood of a car. Polaroid sunglasses operate on the principle that this reflected light will be at least partially polarized perpendicular to the plane of incidence. By orienting the lenses so that their transmission axes are vertical, this polarized reflected light (glare) is mostly absorbed by the sunglasses.
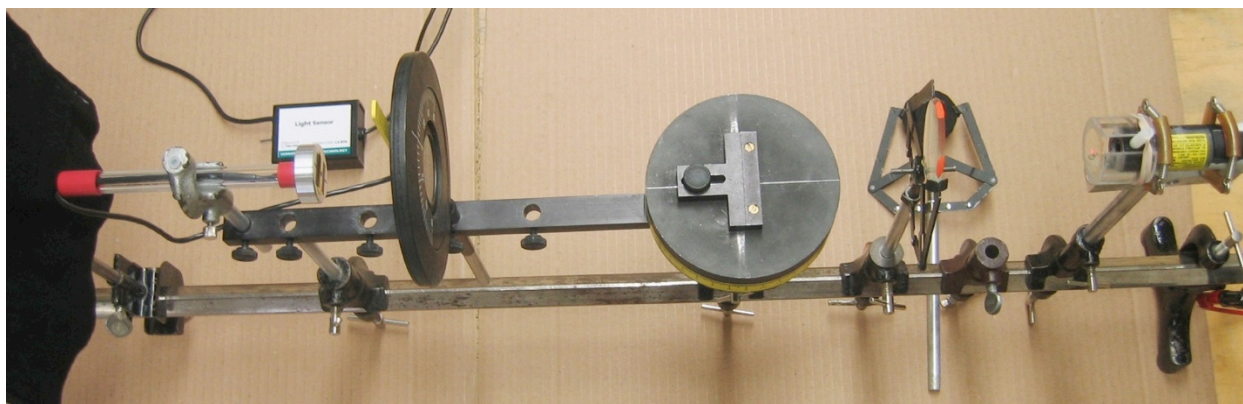
VI. Experiment

Part A. Set up Logger-Pro

1. Everything should already be connected together, but take a look and make sure of the following:
   a. the LabPro interface is connected to its power supply,
   b. the light sensor is connected to CH 1 of the LabPro, and
   c. the USB cable from the LabPro is connected to the computer.

2. Notice that there is a small switch box in the cord that provides power to the light sensor. Find the switch and set the light sensor box to the 0-150,000 lux setting. Each time you choose a different range, a message will show up on Logger pro (if it is turned on).

3. Bring up Logger Pro and make the following initial settings for your experiment:
   a. Look for Logger Pro on the Desktop and start it up by double-clicking on the icon.
   b. A graph page with columns for data from the light sensor will display automatically.
   c.   Click on "USE SENSOR SETTINGS" if it comes up.
   d. The green "COLLECT" button at the top of the screen is used to start each run. If it does not appear, close Logger Pro and start it up again. Also, this button will not light if you try to start a new run while a saved document is on the screen.
   e. Just to the left of "COLLECT" is "DATA COLLECTION". Click on it and choose "LENGTH" equal to 300 seconds. Also, select "OVERSAMPLING".
   f. Depending on the magnitude of the intensity, choose the maximum scale of the graph. You can simply click on the maximum value shown on the axis and modify it accordingly. You can also "AUTOSCALE GRAPH" by clicking on the button denoted by "A" in the same row as the "COLLECT" button.

Part B. Set up the Laser, Beam Blockers, Quarter Wave Plate, Polarizers & Light Sensor

1. To make sensible measurements on polarized light one needs a light-measuring device and a stable light source with a known polarization. We have chosen a Diode laser ($\lambda = 670$ nm) as a light source and a light sensor with an S1133 silicon photodiode, which produces a voltage that is proportional to the incident light intensity.

2.   Set up the laser source, the beam blockers, the quarter wave plate, the 50 cm lens, an analyzing polarizer with rotating mount, and the light sensor and stabilizing rod on an optical bench as in Fig. VI.4 below.
   - Note at this stage there is just one polarizer in place (the analyzing polarizer).
   - Be sure to remove the dielectric reflection plate and place it where it can't get knocked off the bench.

beam blocker	light sensor	stabilizing rod	analyzing polarizer	rotating table	lens	λ/4 plate	laser

Fig. VI.4. *Photo of the experimental setup for verifying Malus's Law at the start of the experiment (note there is only one polarizer in this photo).*

> - **Make sure that the beam-blocking screen is in place 5-10 cm behind the light sensor so that your laser beam will be confined to your own lab bench.**
> - Rotate the laser beam blocker that is closest to the laser out of the beam, and check that the laser beam appears to be parallel with the optical bench.
> - Align the laser beam so that it is centered on the aperture in the mini-screen on the front of the light sensor.
> - **Safety Note: Block the laser beam using the near-laser beam blocker, except when you are performing parts of your experiment that require the laser beam**.
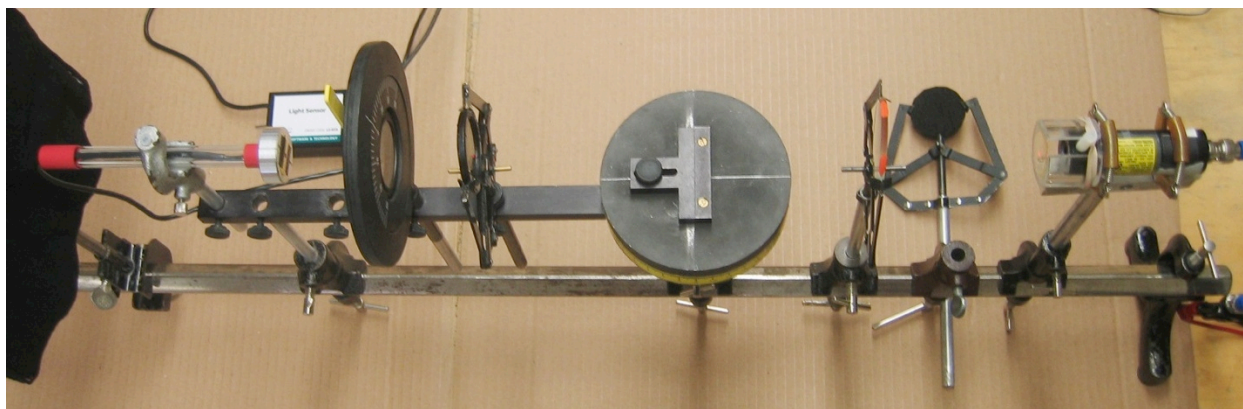
3. In this experiment one needs the light source to be a randomly polarized beam. But, the laser output is nearly 100% polarized. We solved this problem for you by placing a quarter-wave plate in front of the laser and doing an angle alignment to produce circularly polarized light, which will perform in the same manner as randomly polarized light for the purposes of this experiment. To verify that the laser and quarter wave plate are actually aligned properly, start a Logger Pro run and rotate the "analyzing polarizer" several times through a range of about 180°. If the variation in beam intensity is less than about 10%, then no further alignment will be needed. Otherwise set the polarizer at 0° and rotate the quarter wave plate for the lowest power reading on the Logger Pro plot. Again, rotate the "analyzing polarizer" back and forth, just to check.

4. If your apparatus shows more than a 10% variation in intensity when you rotate the "analyzing polarizer", get your TA to check your setup. If it is too far out of alignment the TA will get a Lab technician to readjust the laser.

Part C: Malus's Law Measurements

1. To investigate the transmission of light through two crossed polarizers, you need to insert another polarizer between the analyzing polarizer and the quarter wave plate, as shown below in Figure VI.5. We will call this the "first polarizer".

2. Set the light probe to 0-6000 lux and the Logger-Pro vertical axis to 6000 lux. Choosing the proper range is essential for this experiment. Always choose the "USE SENSOR

| beam blocker | light sensor | analyzing polarizer | first polarizer | rotating table | lens | λ/4 plate | laser |

Fig. VI.5. *Photo of the experimental setup with a second polarizer*

SETTINGS" option if it comes up on Logger Pro.

3. Align the laser with the light sensor so that the laser spot falls exactly into the center of the aperture on the mini-screen on the light sensor. You might need to adjust the height of the sensor.

4. For this experiment, you need to make sure that the polarizers are oriented correctly with respect to each other. To do this, first set the analyzing polarizer to zero degrees. Then click "COLLECT" and rotate the "first polarizer" until a maximum is shown on the screen plot. Now the angle θ read off of the analyzing polarizer will correspond to the angle between the polarizer and the polarization of the light, as required for the Malus's law experiment.

5. Check that the laser light is still falling exactly in the center of the small hole in the light sensor. Otherwise, again carefully adjust the lens, the detector, and the laser until the laser spot exactly hits the center of the small hole in the light sensor.

6. Go to "EXPERIMENT> CLEAR LATEST RUN" for a fresh start. Block the laser so that no light falls on the sensor. Note the reading. This is the ambient light reading. To ensure that this is zero, click on the zero button under "EXPERIMENT".

7. Now record the light intensity as you rotate the analyzing polarizer from 0 to 90 degrees in 5° steps, i.e., at 0°, 5°, 10°, 15°, …, 80°, 85, 90°. At each angle setting, count for a few seconds so that you can see a nice flat section in the plot. Continue in this manner in 5-degree increments until you get a reading for 90°. Then click "STOP".

8. If you are satisfied with the Logger Pro plot of your data, show your TA. Then copy the time and intensity data in the two columns and paste them into an Excel spreadsheet. **Make sure to get all the data in both the time and intensity columns.** Be sure to clearly label these columns.

9. Using your spreadsheet, make a plot of your intensity versus time data.

10. By holding your mouse over a point on your Excel plot, you can read off the intensity at that point. Use your mouse to extract a value for the intensity at each of the angles. Make another small table in excel that just has the angles 0°, 5°, 10°, 15°, …, 80°, 85, 90° in one column and the intensity at each angle in another column. Now make a second plot that shows the intensity versus angle from this table.

10. Add a column to your spreadsheet that shows the theory for how the intensity is expected to vary. In this case, use the equation:

$$I(\theta) = A * \cos^2 \theta + B$$

You will need to choose the fitting parameters A and B so that you get good agreement with your data. Once you have found good values for A and B, add a curve showing the theory to your plot of I versus θ data. You should be able to adjust A and B by hand so that the fit looks good to your eye. Show your TA when you are done.

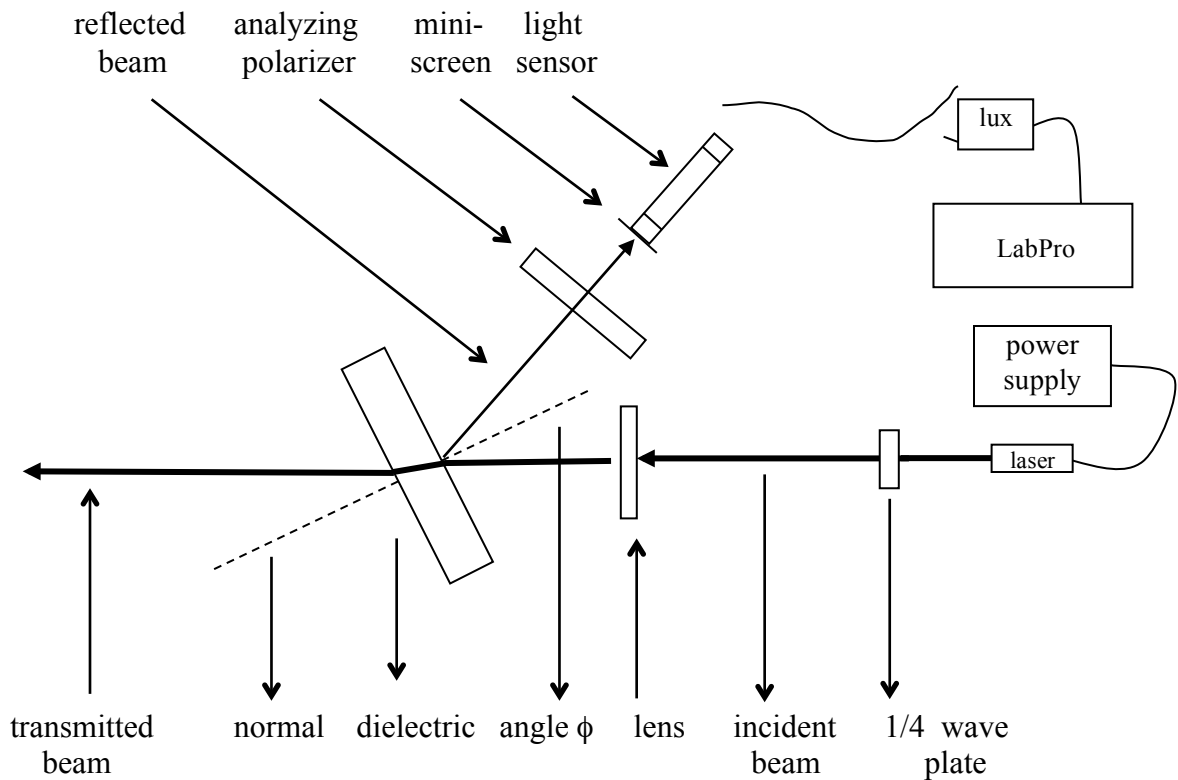## Part D: Polarization by Reflection

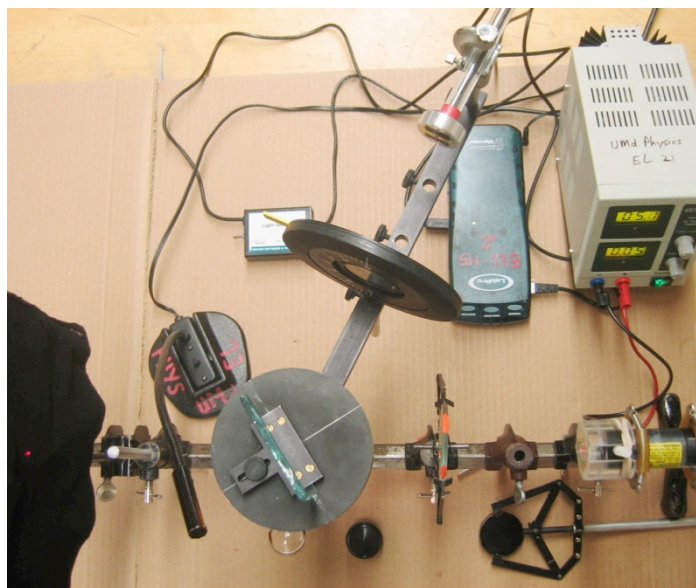**Fig. VI.6** *Sketch of Brewster's Angle Experiment*

Fig. VI.7 *Photo of the Brewster's Angle Experimental setup*

1. In this part you will investigate the polarization of a beam of light reflected from a piece of glass (which is an insulator or dielectric). The angle of incidence, ϕ, is measured using the angular scale of the black rotating table on which the dielectric plate is mounted.

2. Arrange the Brewster's angle apparatus on the optical bench as shown in the Figure VI.6 and VI.7 above. The dielectric plate must be in place.

3. You will first need to calibrate the black rotating table, so that its zero angle will correspond to a zero angle of incidence. Rotate the black circular table until its index mark aligns with the zero degrees mark on the yellow circular table. Use the magnifying glass to aid in precise aligning. Loosen the thumb screw on the optical slider which is supporting the rotating table assembly. While not touching the sharp pointer on the swinging arm, rotate the black and the yellow circular tables together until the laser beam reflects back on itself. Now tighten the optical slider thumb screw.

4. Recall that at Brewster's angle, ϕ_B, the reflected light should be totally polarized perpendicular to the plane of incidence. To find Brewster's angle measure I_{max}, I_{min} and $I_{ambient}$ at angles of incidence of $\phi = 50^\circ$, 52°, 54°, …, 58°, and 60°. At each angle of incidence ϕ, you can find I_{max} by turning the analyzing polarizer until the intensity is

Theta (degrees)	Imax (Lux)	Imin (Lux)	Iambient (Lux)
50			
52			
54			
56			
58			
60			

maximum (this should be near zero), you can find I_{min} by turning the analyzing polarizer until the intensity is minimum (this should be near 90°), and you can find $I_{ambient}$ by using your hand to block the beam. The easiest way to keep track of this data is to enter it into your spreadsheet in a table that looks like the following:

6. For each angle, find the percent polarization. To do this, add a column to your spreadsheet for $(I_{min}-I_{ambient})/I_{max}$.

7. Make a plot of the percent polarization versus the angle of incidence. From your plot, estimate Brewster's angle, ϕ_B, for this piece of glass. From your plot, also estimate the uncertainty in your value of ϕ_B.

8. Calculate the index of refraction for this piece of glass using $n=\tan\phi_B$

VII. Final Questions

Keep your lab report brief. Include the answers to the following three final questions in your spreadsheet - just type them into a cell.

1. Compare your plot of the data to your plot of the fitted curve. How well do your results agree with Malus's Law? Don't just say it agrees or does not agree, explain why you are saying it agrees or does not agree.

2. How well does your measurement of Brewster's angle agree with the value you would expect if the glass has n = 1.50? Don't just say it agrees or does not agree, State clearly what you measured and what you expected and then explain why you are saying your result agrees or does not agree.

3. Give two possible reasons why the reflected light intensity does not quite reduce to zero at Brewster's angle in the apparatus you used today. Explain your answers briefly.

When you are all done answering the final questions, upload and submit your spreadsheet to ELMS Blackboard.