Ay 105 Lab Experiment #P: Polarization!!!!

<u>Purpose</u>

In the first week's lab you used a very simple optical set up to produce collimated light which was then focused on to (part A) or overilluminating (part B) a detector. In this lab, you will start with a similar collimated light source but increase the complexity of the optics, incorporating both mirrors and lenses. You will study the properties of telescopes, eyepieces, and field lenses used in multiple element optical systems. A main goal is to learn how to relate angular and linear quantities.

Unlike the first week, there are no drawings given to you in this week's lab instructions, nor is the equipment and its setup described in as much detail. You are learning how to figure things out yourselves! However, as initial help, there may be some equipment set up on each bench. You will spend the first day with one setup (Part A or B), then switch places for the second day.

<u>Pre-lab Work</u>

- Review the concepts of polarization. Understand the concepts of linear, circular, and elliptical polarization.

- Understand polarizing elements.

- Remember how to do matrix multiplication

<u>Background</u>

Light waves have two independent directions of interest; one is their direction of propagation and the second is the direction of the electric field (the magnetic field is perpendicular to both). The direction of the electric field is often referred to as the polarization direction.

There are different "basis vectors" for which you can express polarization. Vertical, horizontal, left circular, and right circular. Linear polarization can be thought of as a combination of right and left circular polarization. For example, vertical polarization is a combination of right and left circular polarization exactly in phase and with equal magnitude; horizontal would be left and right offset by 90 degrees. The most general form is elliptical, where the left and right circular polarizations have both different magnitudes and phases.

We often speak of "unpolarized" and "polarized" light, but these expressions, particularly "unpolarized," are considered harmful. *Every photon is completely polarized.* However, we often don't detect single photons, but bunches of them. Depending

on the emission mechanism and the intervening material, streams of photons may be have polarizations that vary randomly (stochastically) and we then say the light is "un-polarized". On the other hand, some emission/absorption mechanisms produce light that is always polarized a particular way, which is then referred to as "polarized" light.

<u>Equipment List</u>

QTH lamp
Lens (2 of these 50 mm Diameter, any focal length you like)
Film polarizers (2)
Glass polarizers (1)
Power Supplies
Diffuser
Aperture stop
Photodiode
Rotational *mount* (not stage)

<u>Experiment</u>

Part A : Malus' law and the Jones' matrices
In this experiment, you will polarize a light beam and examine how the intensity changes with polarizer angles. **Part A Configuration and Measurements**
Set up an optical rail with a QTH lamp on one end and a photodiode on the other end. Put in a lens to collimate the beam and use a pupil to stop it down to about 1", and add a lens at the end to focus it onto the photodiode.

For all of the following, be careful to quantify your errors, particularly your main sources of error.

1. Measure the intensity of the QTH lamp on the photodiode, then block the photodiode to get a sense of your zero point.

   In the path of the collimated beam, add a cheap film polarizer. Verify that the output is cut down by 50%.

   Add a second (nice) polarizer on a rotating stage. Mount the polarizer so that the intensity is minimally attenuated, which will occur when the polarizers are aligned. *Record at what angle this occurs; this is your "zero" position.* Leave enough room for a third polarizer!

   Measure the output flux as a function of polarizer rotation angle as you rotate around a circle. Move the rotational mount in 5° increments. Record your intensity outputs.

2. Remove the rotational stage completely. (*Don't take it apart. Just take everything completely off the rail*) Replace it with a film polarizer aligned 90° to the first film polarizer. Measure the photodiode output (it should be at about a minimum).

Now, insert the rotational mount *between* the two film polarizers. Set it to the original "zero" position, and repeat the intensity measurements at 5° increments.

Part A Analysis. Calculate the expected intensity for each of the two cases above using the Jones' matrix formalism and compare it to your experiment. You may want to use a computer algebra system or write a little program. Assess your results and comment on any discrepancies. Also, please note if you can think of a way to improve the experiment.

Part B : Optical Activity
Introduction

The index of refraction arises from photons' interactions with the constituent atoms/molecules of a material; in particular, there is a phase shift that occurs with each atomic/molecular interaction, and thus the phase velocity increases or decreases in proportion to the number of interactions (in other words, the length of the material).

As you might expect, if the structure of a material is not exactly symmetric in every direction, a photon can react differently depending on its polarization and path through the material. In other words, the index of refraction is polarization dependent. This phenomenon is known as *birefringence*. We don't often notice this because most light we see is randomly polarized, and our eyes are not sensitive to polarization.

The interstellar medium has a different index of refraction for right and left circular polarizations as well, depending on the electron density and magnetic field. Pulsars produce highly regular, polarized emission, and by measuring the rotation of the pulses, you can map out the magnetic field of the ISM. This is basically the only way we have to measure the interstellar magnetic field.

More easily, this effect can be noticed with some crystals (such as calcite, where you see two images when you look through it), but it also occurs in non-crystalline structures which have a particular *chirality*. In this case, the index of refraction is different for left and right circularly polarized waves. Linearly polarized light, which is composed of equal parts left and right circularly polarized light, will then rotate as it passes through a material. The full analysis of this phenomenon is rather complicated and requires hardcore QED. If you manage to work it out, you can get 1 extra point.

The *specific rotation*, given in degrees/10cm/(grams/mL), quantifies the rotational strength of the material.

$$[\alpha]_\lambda^T = \frac{\text{polarization angle change}}{(\text{path length}/10 \text{ cm})(\text{grams/mL})}$$

Note that this is dependent on wavelength and temperature. In this lab, we will measure the specific rotation of a number of substances.

Part B Configuration. Lasers are (usually) polarized and make decent light sources. You will shoot a laser through a linear polarizer (just to be safe!), the substance in question, a rotatable polarizer, and focus it onto a photodiode. By adjusting the angle of the rotatable polarizer, you will be able to find the angle of maximum intensity, which will correspond to the polarization angle of the light. This gives you one data point. By adjusting the concentration of the material, you can get more data points.

Equipment List

Laser
Lens (1 of these, 50 mm Diameter, any focal length you like)
Film polarizers (1)
Glass polarizers (1)
Power Supplies
Photodiode
Rotational *mount* (not stage)
"Optical Cavity"

Part B Setup and Measurements.
Set up a rail with a laser at one end. Make sure you are able to rotate the laser on its mount. Add the cheap polarizer on a square mount in front of the laser. On the other end[1] mount the lens and photodiode and focus the laser onto the photodiode. Rotate the laser so that it's in line with the polarizer (ie, maximum intensity on the photodiode), and lock it in place.[2] Next, set up the rotational mount/round polarizer and orient it so that it is in line with the laser and first polarizer. (Check that the intensity is about the same as without it and *record this position!!*). Fill the "optical cavity" with (a fixed, measured amount) of water and place it in the path of the laser so that the laser passes through it, and verify that the laser is still focused onto the photodiode. Make a note of whether the water rotates the polarization of the laser light. For the following, be careful to guarantee that the laser is always passing through the same amount of solvent.

At this point, you will add different amounts of liquids or solids into the water and measure the angle of maximum intensity (corresponding to the polarization angle.) Start with a table sugar, and keep track of how much you are adding to your water solution. You will have to take care to dissolve the sugar in the water, so perhaps using warmer water will help. Also, for substances like milk (ie, lactose), be sure to keep track of the amount of lactose in your solution (by looking at the nutrition facts).

You should note that a specific rotation of 270° and -90° (for example) are indistinguishable with a single measurement, so you will need to make multiple measurements to get a sense of what the specific rotation is.

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[1] it doesn't have to be all the way at the end of the rail

[2] I don't know how good this laser is at keeping polarization fixed. Let me know if the polarization flips randomly. That is bad.

Part B Analysis. For each substance, measure the rotation angle of a number of different concentrations and derive the specific rotation from these numbers. Keep a note of your errors and the goodness of fit for each of these samples. Additionally, make a note of the chirality of each of the substances in question. How does this compare with the specific rotation direction??

Part C: The Fresnel Equations and Polarization
Introduction

The Fresnel equations describe the reflection and transmission of light when passing from one medium to another. They are of fundamental importance in optics. They are given by the following:

$$R_s = \left| \frac{n_1 \cos\theta_i - n_2 \cos\theta_t}{n_1 \cos\theta_i + n_2 \cos\theta_t} \right|^2 = \left| \frac{n_1 \cos\theta_i - n_2 \sqrt{1 - \left(\frac{n_1}{n_2}\sin\theta_i\right)^2}}{n_1 \cos\theta_i + n_2 \sqrt{1 - \left(\frac{n_1}{n_2}\sin\theta_i\right)^2}} \right|^2$$

$$R_p = \left| \frac{n_1 \cos\theta_t - n_2 \cos\theta_i}{n_1 \cos\theta_t + n_2 \cos\theta_i} \right|^2 = \left| \frac{n_1 \sqrt{1 - \left(\frac{n_1}{n_2}\sin\theta_i\right)^2} - n_2 \cos\theta_i}{n_1 \sqrt{1 - \left(\frac{n_1}{n_2}\sin\theta_i\right)^2} + n_2 \cos\theta_i} \right|^2$$

Where

- $R_{p,s}$ are the intensity reflection coefficients of the s or p-polarized light

- $n_{1,2}$ are the indices of refraction of the different materials

- $\theta_{i,t}$ are the incident and reflected wave angles, as measured from the normal

The notation s, and p polarized refers to waves which are polarized parallel and perpendicular to the medium in question.

In this lab, you will measure the reflection coefficients for s and p polarized light off of a piece of plate glass ($n=1.5$).

Part C Configuration. Lasers are (usually) polarized and make decent light sources. You will shoot a laser through a linear polarizer (just to be safe!), and off of a piece of glass at different angles and measure the intensity of the reflected beam.

Equipment List

Laser
Film polarizers (1)
Rotational stage (2)
Power Supplies
Photodiode
Plate glass

Part C Setup and Measurements.

Note: This experiment is quite sensitive to stray light, so it is recommended you do it in darkness)

Also, *keep track of your error sources!!!* Fix a laser on an optical table and point the beam at the rotational stage with a piece of plate glass mounted in the middle. Align the beam so that the reflection off of the glass is in the same plane as the laser (ie, when you rotate the stage, the reflected point should not change in the z-direction (*it is very important that this part is done carefully!*).

Add a polarizer (in the vertical, *s* direction) in between the laser and the rotating stage and make sure the two are aligned. Measure the output of the laser and rotate it so that it is maximized (ie, the laser is in line with the polarizer). Record the laser output through the polarizer before it hits the plate glass.

In principle, all you need to do is measure the output of the reflected beam. However, keep in mind that the intensity of the photodiode is sensitive to the input angle of the laser beam (to the tune of $\cos\theta$), as you found out in your first lab. One way to correct for this is to mount the the photodiode on a rotational stage aligned to the screw holes on the breadboard and exactly offset the angle (the angle will be *twice* the angle of the piece of glass) and slide it around until you intercept the laser beam. Align it as best you can with the screw holes, but don't screw it down; that would take too much time.

Doing this, measure the output intensity from as close to 0° as you can through as close to 90° as you can. Be sure to calibrate the photodiode with a dark measurement, as you did in previous labs.

Repeat this measurement by rotating the laser *and* polarizer 90° degrees to get the other polarization (the *p*-direction).

Part C Analysis

Plot the two reflection coefficients for plate glass, and see how well your data matches. You may have to float the initial intensity, but you are free to consider how best to perform your analysis. What are your main sources of error (systematic and statistical)? How do those propagate in the equations?

<u>Discussion</u>

Concisely summarize what you've learned in this lab about polarization. Make specific comments about how the labs could be improved.