Polarization of Light

Introduction

Did you ever wonder how sunglasses actually work? Light emitted from an object (whether it be the Sun or a fluorescent source) or reflected by a shiny surface consists of oscillating electric and magnetic fields that are perpendicular to each other. The orientation of the electric and magnetic fields is such that they oscillate perpendicular to the direction in which the light wave travels. This means, for example that portions of the electric field can be blocked or filtered to reduce the intensity of the traveling light wave. Sunglasses use a film that effectively blocks light with a certain orientation, or polarization.

In this lab, you will investigate the nature of light and how the polarization can be manipulated to control the direction and intensity of a light source.

Equipment

- Three Circular Polarizers
- Dual Square Polarizer Assembly
- Incandescent Light Source
- Lab Pro and Light Sensor
- 1.2 Meter Optical Bench
- Two Adjustable Lens Holders
- Small Calculator
- Plexiglas & Polycarbonate (U-shaped) Samples
- Solar Cell

Background

Light is a wave composed of oscillating electric ($\vec{E}$) and magnetic ($\vec{B}$) field vectors that are perpendicular to each other and to the direction of propagation (Figure 1). If light is traveling in the z-direction, the $\vec{E}$ and $\vec{B}$ fields are in the x-y plane.

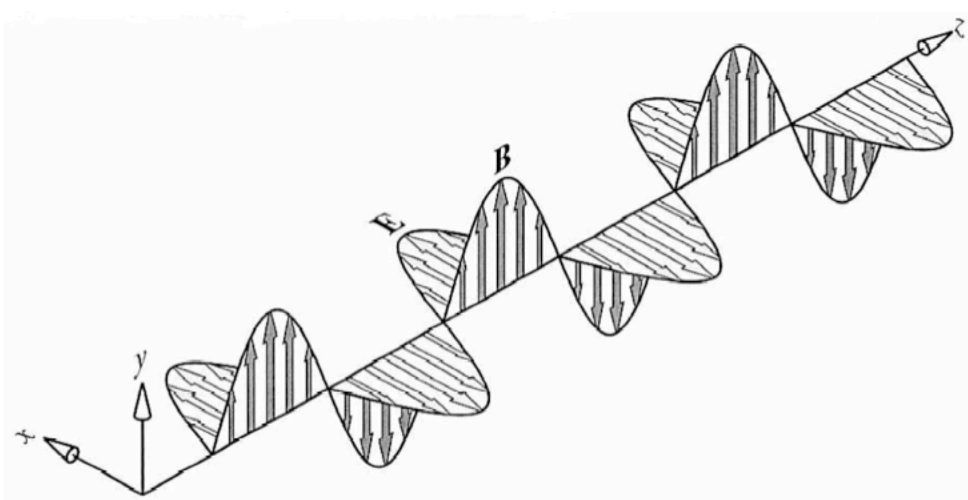

Figure 1: Electric & Magnetic Vector Components of Light

If, for example, we knew that the direction of the oscillating electric field ($\vec{E}$) were along the x axis, then the magnetic field ($\vec{B}$) must be perpendicular to it in the x-y plane, which would put it along the y axis. If the electric field $\vec{E}$ points only in the $+x$ or $-x$ directions (since it is oscillating, if it points along $+x$ now, it will point along $-x$ one-half period later), the light is said to be plane-polarized along x. If $\vec{E}$ were along $\pm y$, the light would be plane-polarized along y.

For the sake of simplicity, $\vec{E}$ is frequently considered to lie along an axis, but it can point in any direction in the *x*-*y* plane. Since it is a vector, we can represent it as a the sum of its *x* and *y* components:

$$\vec{E} = \hat{i}E_x + \hat{j}E_y$$

In the case of unpolarized (random) light, all the directions are equally represented, and all the directions can be resolved into their *x* and *y* components. A polarizer aligned to pass light oriented in the *x*-direction will filter out all the components in the *y*-direction. We stress components to reinforce the idea that this is a vector situation - only one-half of the unpolarized light entering a linear polarizer gets through.

This is not the same as white light that encounters a colored filter (say, a red filter), which will only allow red light to pass through. A perfect linear polarizer lets exactly one-half of randomly oriented (unpolarized) light through, because all light can be resolved into directions either parallel to or perpendicular to the direction of the polarizer.

Procedure

Effects of a Single Polarizer

Your kit includes two to three circular polarizers in aluminum frames with notched edges marked at 15^O intervals. These polarizing filters (similar to the material of Polaroid-brand sunglasses) have long-chain molecules that are aligned parallel to on another. The net effect is that one polarization of light (the one with $\vec{E}$ parallel to the long molecules) is 99% absorbed while 50% of the other polarization is transmitted.

- Look at an unpolarized light source through one of the circular polarizers.
- Rotate the single polarizer until it has completed at least a 360^O rotation.

Notice that the light intensity does not vary as the polarizer is rotated. This shows that the source is sending out waves with every orientation of $\vec{E}$ in equal amounts. Such a source is said to be unpolarized: the light coming out of the polarizer is plane-polarized along the polarizer's transmission axis, which is indicated by the red index mark on the outer rim of the polarizer.

Now use the Lab Pro equipment to determine how much light actually makes it through a single polarizer.

- Place the light bulb and the light sensor at opposite ends of the 1.2-meter optics bench. Use the provided ring stand w/clamp to steady the light sensor. Plug the Light Sensor into one of the analog ports of the LabPro interface.
- As you did in the RC Circuits lab, open up a digital meter in LoggerPro to display the measured values of the intensity of the light coming from the bulb.
- Turn on the light bulb, and record the unfiltered output of the light bulb as recorded by the light sensor.
- Using an adjustable lens holder, place the polarizer in between the bulb and the light sensor (as close to the light sensor as possible) and repeat the previous step.
- Use the values for the unfiltered & filtered measurements to determine (by percentage) how much light is being blocked while the polarizer is placed in between the bulb and the sensor. For instance, if your unfiltered reading is 100 lux, and your filtered reading is 55 lux, then 55% of the light passed through the polarizer to the light sensor.

Effects of Two Polarizers

Figure 2 shows the easy axes ($\vec{E}_1$and $\vec{E}_2$) of the two polarizers. "Easy axis" means that components of the electric field that are aligned with this axis pass easily through the polarizer. The light that is transmitted through the first polarizer is plane polarized along direction $\vec{E}_1$. Suppose the polarizers are rotated by θ, where θ is the angle between their light-transmitting axes. Now, the only component that will pass through the second polarizer is the component along $\vec{E}_2$. By trigonometry the amplitude of this component is proportional to cos θ. Since the intensity of any wave depends on the square of its amplitude, the transmitted intensity varies as $\cos^2 \theta$.

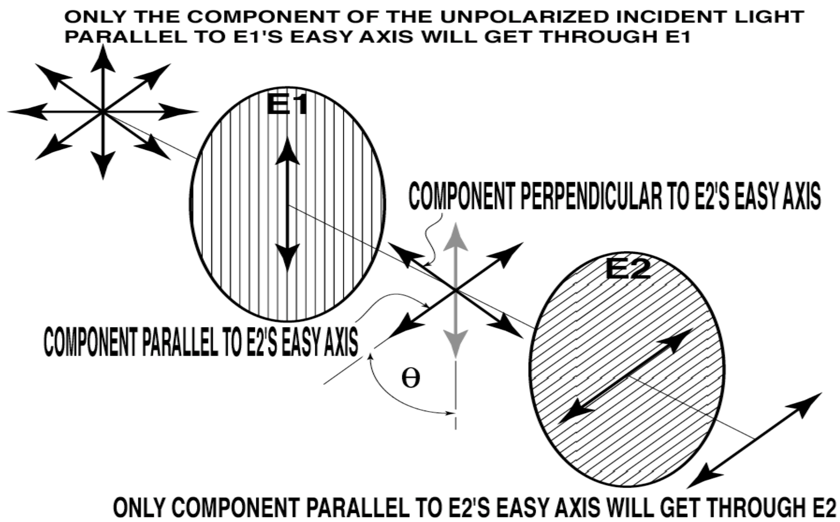

Figure 2: Effects of Light Passing Through Two Polarizers

- Look at a light source through the two round polarizers, holding the one closest to your eye in place while rotating the one furthest from your eye.
- As the further polarizer is rotated, the amount of light that passes through both polarizers will vary, going from light to dim and back to light.

Now use the Lab Pro equipment to determine how much light actually makes it through a two-polarizer system.

- Place each of the circular polarizers into an adjustable lens holder.
- Arrange the equipment so that the Light Sensor is at one end of the optics bench, and the polarizers are placed close to the Light Sensor, with 3-6 inches of space in between first and second polarizer, and between the second polarizer and the Light Sensor. Place the light bulb about 6 inches in front of the polarizer furthest from the Light Sensor.
- Record the amount of light that gets through both polarizers.
- Keeping the polarizer closest to the Light Sensor in a fixed position, rotate the polarizer closest to the light source by about 45^{O} and again measure the amount of light that passes through both filters.
- Continue rotating the front polarizer by 45^{O}, recording the amount of light passing through, until you have rotated the front filter by a full 360^{O} turn.

Describe the number of maxima and minima that you observed in the exercise, and explain when the two extreme interference conditions occur in terms of the relative orientation of the easy axes for the two polarizers.

Effects of Multiple Polarizers

Your kit contains two square polarizers that are mounted together. The polarizers are "crossed", i.e., their easy axes are at right angles to one another.

- Use the Light Sensor (as before) to determine how much light is blocked by the square polarizer pair.
- Place one of the circular polarizers either in front of or just after the crossed pair, and note any change in the percentage of light transmitted. Does rotating the circular polarizer have any effect on the amount of transmitted light?
- Now place the circular polarizer in-between the crossed pair and rotate it through a full 360^{O} path (Figure 3); you will not need an adjustable lens holder to do this. Does the amount of light transmitted stay the same, decrease, or increase?
- Begin to rotate the circular polarizer in between the two square polarizers. Record your data on a graph so that you can determine at what point (and how much) the transmitted light varies as you rotate the circular polarizer.
- In your notebook, explain your observations and justify how the light intensity can vary as the circular polarizer is rotated between the crossed polarizers. Hint: think about how the light is polarized after passing through each polarizer and its orientation relative to the next polarizer it encounters.

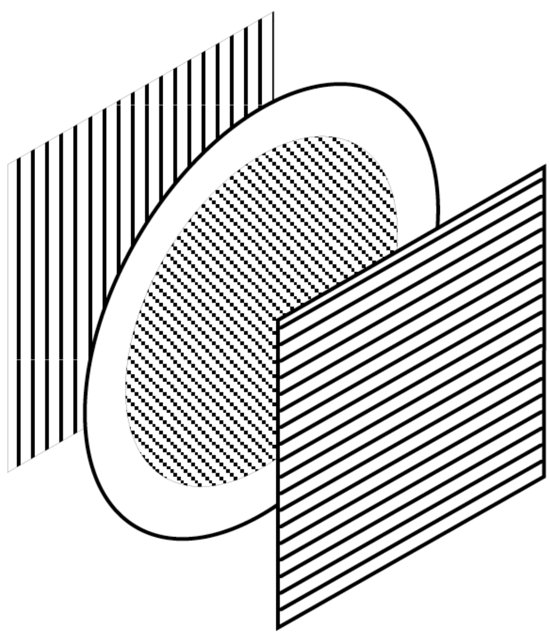

Figure 3: One Circular & Two Square Polarizers

Only materials that treat the two polarizations differently can result in light transmission when viewed between crossed polarizers. Ordinary materials (water, for example) appear completely dark between crossed polarizers. Glassblowers routinely examine their work between crossed polarizing filters. Regions of stress show up as bright spots in an otherwise dark image. The glassblower will then gently heat the piece, to allow the stressed region to relax.

The following qualitative exercises are examples of phenomena that are only visible with crossed polarizers.

- Hold a plexiglas "U" between crossed polarizers with a light behind them.
- Squeeze the plexiglas with your fingers. You will notice light is transmitted in the regions of highest stress (near the bend in the "U"). The stress causes the long molecular chains to be slightly

aligned in one direction more than others, resulting in the polarization of the light passing through it.

- Now use the piece of polycarbonate. You will see colors changing when you squeeze it. Also, even in the un-squeezed condition, you will notice a color. The long molecules of polycarbonate are partially aligned by being pressed between rollers during manufacture.
- Your kit has a small calculator with a liquid crystal display (LCD). The front window, a sheet of polarizer, has been removed. As you turn the calculator on, you will not see anything with the front window missing. Put a single polarizer in front of your eye; as you rotate the polarizer (or the calculator), the display goes from dark numbers on a light background to light on dark.
- Lastly, instead of putting the polarizer near your eye, use it to polarize the light falling on the display - the numbers should then appear. A side view of a liquid crystal display is shown in Figure 4. The two polarizers are crossed for normal dark-letters-on-white-background.

Figure 4: Cross-Sectional Views of an LCD Display on a Calculator

Polarization by Reflection

Consider light incident on a glass sheet (Figure 5). Some light is reflected (*r*) and some is transmitted (*t*). This is in accordance with Snell's Law of Refraction, which describes the bending of light when it passes from one medium into another:

$$\frac{n_i}{n_t} = \frac{\sin(\theta_i)}{\sin(\theta_t)}$$

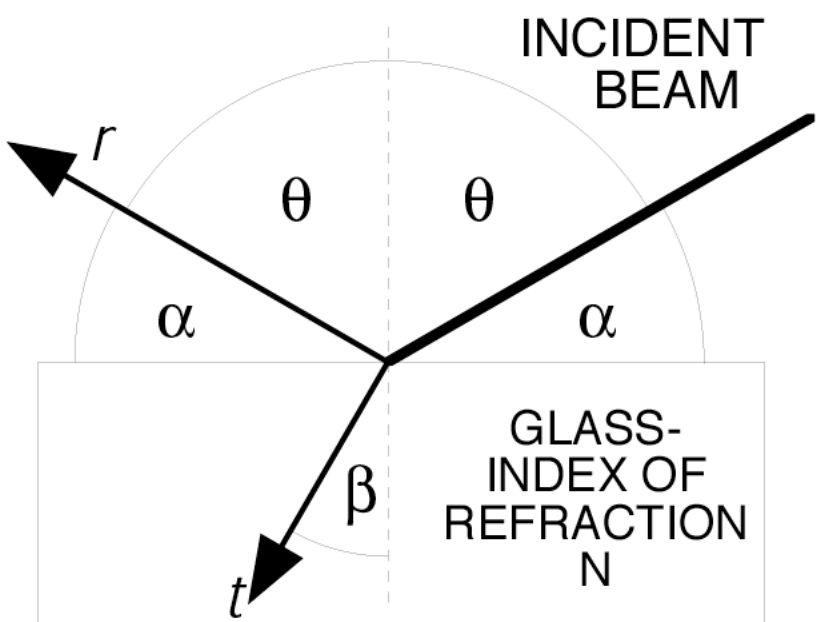

Figure 5: Representation of Snell's Law

For the specific angle of incidence (θ_i), the reflected light will be completely linearly polarized (the electric field will be perpendicular to the plane of the above sketch, oscillating in and out of the page). Although we do not derive it here, if θ_i is set to Brewster's angle (θ_B), there will be no reflected light (and 100% transmitted light) for one of the two polarizations. This is an easy way to polarize light without the types of filters that you've used to this point.

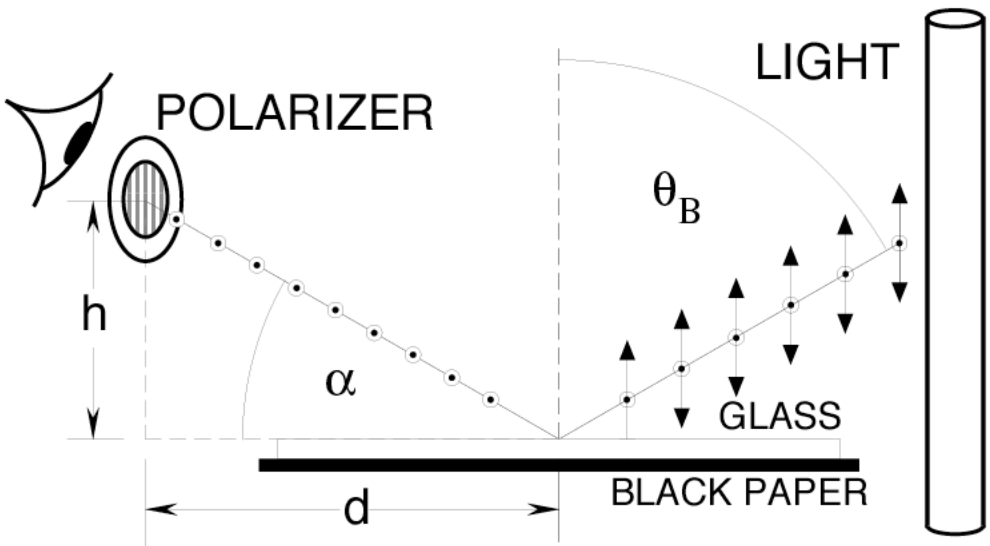

Figure 6: Representation of Brewster's Angle

Brewster's angle (θ_B) represents the state such that the reflected and transmitted beams are perpendicular to each other:

$$\theta_B + 90^o + \beta = 180^o$$
$$\theta_B = 90^o - \beta$$
$$\cos\theta_B = \cos(90^o - \beta) = \sin\beta$$

Snell's law relates θ_B and β by

$$1 \cdot \sin\theta_B = n \cdot \sin\beta$$

where the index of refraction of glass is n (the index of refraction in air is one). Substituting into Snell's law we have:

$$\sin(\theta_B) = n\cos(\theta_B)$$
$$\tan(\theta_B) = n$$

The index of refraction for glass is approximately 1.5, so θ_B is about 60^O, meaning α (the angle from the surface to your eye) is near 30^O. We use these approximate values just to help find the effect.

- Look at the reflection of the vertical fluorescent tube from the glass plate on the table as you rotate a polarizer in front of your eye (see Figure 6 above). Start at a position such that the angle, α, in the figure is about 30^O.
- For one orientation of the polarizer, much of the reflection will be filtered out. Hold the polarizer in that position and examine the image more closely.
- Move around to find the position where one part of the image completely disappears; the light will be completely polarized perpendicular to polarizer in your hand when you are viewing the darkest image.

- Measure *d* and *h*, and use that information to calculate α.
- Calculate the index of refraction, *n*, of the glass. If your value of *n* is very different from 1.5, you have made an error. Re-check your procedures, and if need be, ask your TA for assistance.

At angles close to Brewster's angle, the reflected light is more horizontally (*H*) polarized than vertically (*V*) polarized. Polaroid-type sunglasses are made to absorb *H* polarization and allow *V* to pass through. While only one-half of the direct light reaches your eyes, considerably less than one-half of the glare passes through the glasses. They are most useful in the presence of brightly illuminated, highly reflective surfaces such as automobile glass, water or snow. Explain how you could determine if a pair of sunglasses has polarized lenses using equipment that you have available to you in this lab.

Polarization by Scattering

The clear sky is blue because of light scattered by individual gas molecules. Such scattered light is also polarized. If it is a clear day, look at the outdoor sky through one of the circular polarizers, 90^{O} away from the sun, as shown below. (Helpful hint: Never look directly at the sun...with or without a polarizer). You will find the blue light is highly polarized, though white or grey clouds are not. If it is an overcast day, you will produce the effect of clouds by using a beaker of water that has been mixed with a small amount of coffee creamer.

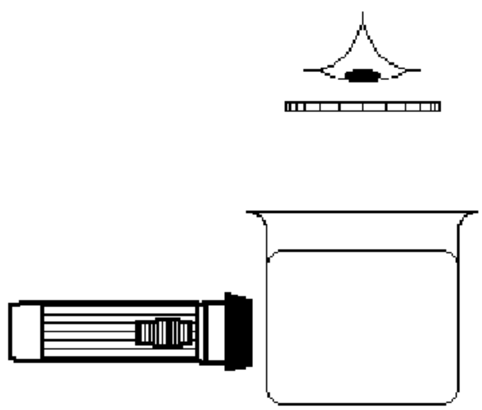

Figure 7: Simulation of the Polarization of a Cloudy Sky

- Place the flashlight on the table so that it shines through the beaker from the side (Figure 7).
- View straight down into the beaker using one of the circular polarizers.
- Rotate the polarizer as you observe the water in the beaker.

What happens to the intensity of the light as you rotate the polarizer? Is this the same effect that you saw in previous cases?

Verification of $\cos^2 \theta$ Law

Earlier, you qualitatively verified the $\cos^2 \theta$ law, known as Malus's law, by noting the light and dark appearances for varying amounts of rotation between two polarizers. Now you will use a solar cell (silicon photovoltaic cell) to detect the light intensity. Figure 8 shows the experimental set-up for the portion of the lab. A multimeter will measure the solar cell's current, which, conveniently for our purposes, is nearly proportional to the light intensity.

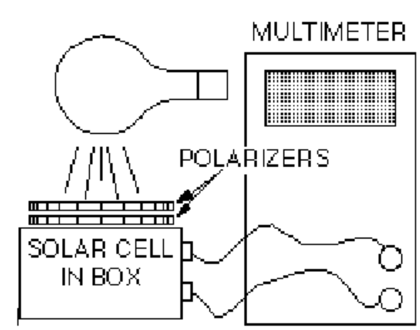

Figure 8: Experimental set-up for the quantitative confirmation of Malus's law for crosses polarizers.

- Measure and plot the current as a function of the angle, θ, between the two polarizers, for $0^{O} \leq \theta \leq 180^{O}$, in steps of 15^{O} or less.
- Fit a function of the form $B \cos^2 \theta$ to your data, where B is a constant chosen to agree with the data at $\theta = 0$. Discuss how well your data agree with the theoretical predictions of Malus's law.

Concluding Questions

When responding to the questions/exercises below, your responses need to be complete and coherent. Full credit will only be awarded for correct answers that are accompanied by an explanation and/or justification. Include enough of the question/exercise in your response that it is clear to your teaching assistant to which problem you are responding.

1. Polarizers are sometimes referred to as filters. Explain why this is an appropriate name for polarizing materials.
2. If you had a single polarizer, how could you determine whether or not light from a room light was polarized when emitted from the bulb?
3. Suppose that you have one polarizer with its polarization direction marked. If you were given a second unmarked polarizer, explain how you could determine the polarization direction of the unmarked polarizer. Explain your reasoning.