Lab 5: Polarization of Light

1   Introduction

In this experiment, we will study the effects of polarizing media on randomly polarized light from an incandescent bulb. Linear polarizing filters, dielectric reflecting surfaces and birefringent materials all affect the polarization of light waves. This effect can be used to great advantage both to obtain light beams with a desired kind of polarization and as a means of studying the polarizing medium itself.

2   Linear Polarization

The polarization of an electromagnetic wave refers to the orientation of its electric field $\vec{\mathcal{E}}$. The light from most natural sources is, in general, randomly polarized. This means that the direction of $\vec{\mathcal{E}}$ is randomly varying with time on a very fast scale. The light from an incandescent bulb, for example, emits a mixture of light waves with electric field components that change randomly on a scale of 10^{-14} s, almost as fast as the optical frequency itself. A linear polarizer is a device that only allows electric field components parallel to a certain direction (called the polarization axis) to pass through. Any light that comes through such a polarizer is polarized in the direction of the polarization axis. After leaving the polarizer, the light wave's polarization ($\vec{\mathcal{E}}$-field direction) does not change, as long as it merely travels through air, and the light is said to be linearly polarized.

If the linearly polarized light passes through a second polarizer, the transmitted intensity $I(\theta)$ of the light as it leaves the second polarizer, is given by Malus' Law

$$I(\theta) = I_0 \cos^2 \theta \tag{1}$$

where I_0 is a constant (equal to the intensity of the light leaving the second polarizer when the polarization axes of the two polarizers are parallel) and θ is the angle between the polarization axes. This is completely consistent with the Jones matrix for polarizers at a relative angle θ.

3   Procedure

Set up the optical bench with the incandescent light source and photometer about 50 cm apart. Once you have established this setup, do not move the source and photometer relative to one another.

Question 1: Explain why you should not move these. What happens if you do?

Measure the intensity of the light with the photometer with no polarizers present. Now put one linear polarizer between the source and photometer and measure the intensity again.

Question 2: What is the result? Why? Does it vary as you rotate the polarizer?

Place a second polarizer between the source and photometer. Rotate the second polarizer while keeping the first one at a known and fixed orientation. Record the intensity of the light reaching the photometer as a function of the angle of the second polarizer relative to the first. Graph your results and explain what is going on, and be sure to include measurement uncertainties. Now rotate the original polarizer and repeat your measurements.

Question 3: How are these results different from the earlier ones? Explain why.

Next, interchange the two polarizers, and repeat the two experiments above. Explain how your results are consistent with the Jones matrices for the four cases, given that matrix multiplication is non-commutative.

Arrange the two polarizers to provide minimum intensity and note their orientation. Now add a third polarizer between the first two, and measure the intensity as a function of the orientation of the middle polarizer as you rotate it, keeping the other two fixed. Graph your results and explain. Calculate what you'd expect using the Jones matrices, and compare with your measurements. Discuss the discrepancies.

Question 4: Use the Jones matrices to show that what you observe in this case is what you might expect.

4 Circular and Elliptical Polarization

Certain crystals are optically asymmetric, having a particular optic axis, defined by the crystal structure, with the following interesting property: light polarized parallel to the optic axis experiences a different index of refraction (and therefore has a different velocity) than light polarized perpendicular to the optic axis. Such crystals are called birefringent, and can be used to make a retarder, such as the one in your optics kit.

Question 5: Explain why it is called a retarder.

The optic axis of your retarder is marked on the scale around the edge, and is designed so that light polarized parallel to this axis travels a different optical path length than light polarized perpendicular to it. This results in a relative phase shift between waves of the two polarizations. Your retarder causes a phase shift of $\pi/2$, or a quarter of a wave, and so it is often called a quarter-wave plate $\lambda/4$.

5 Procedure

Replace the middle polarizer with a quarter-wave plate. Rotate the linear polarizer closest to the photometer (this polarizer is often called the analyzer) and record the intensity as a function of the analyzer angle. Also record the orientation of the quarter-wave plate. Do this again for different orientations of the quarter-wave plate. In particular, find an orientation for the quarter-wave plate for which the transmitted intensity is independent of analyzer angle.

Question 6: What kind of polarization is this?

The orientation angles should all be measured relative to the transmission axis of the first polarizer. For each set of data that you plot, use the Jones matrices to derive the theoretical curve and plot it on the same graph.

6 Qualitative Examples of Polarization and Birefringence

There are several materials available for this lab that exhibit polarization and/or birefringence.

Calcite. If the optic axis of a calcite (*aka* Iceland spar) crystal is oriented properly, and the crystal is placed on a piece of paper with printing on it, as you look through you will see a double image of the letters. Upon rotating the crystal, one of the images will stay fixed, while the other rotates with the crystal. The stationary image is called the ordinary image, while the rotating one is called the extraordinary image. Place the crystal flat on a printed page and observe the images of the letters. Decide which is ordinary and which is extraordinary. Using a linear polarizer, describe the polarization of each image. Explain the origin of these two images.

Polaroid Sunglasses. Make yourself a pair of sunglasses by holding two polarizers up to your eyes. Try them out in the hallway. How do you have to orient them to reduce the glare from the floor? How do you have to orient them to reduce the glare from the walls or windows? Explain.

Stress Birefringence. Brewster discovered that birefringence could be induced in normally non-birefringent materials by the application of stress. If transparent objects are placed between two polarizers and viewed with white light, they can exhibit birefringence and we will see colors and patterns related to the stresses in them. This can be used in manufacturing to reveal stresses in products, which may point to production flaws.

Question 7: Why are there colors??

Try placing the following materials between two polarizers and observing the transmitted light:

- Pieces of scotch tape, perhaps stuck to a glass plate

- U-shaped piece of plexiglas (try squeezing it)

- Pieces of a plastic bag (try stretching it)

- Similar materials, as available.