Lab 15

Polarization of Light

Continuing Objectives

4. Be able to make careful measurements to ensure reproducible results.

6. Be able to make a good graph, either in your notebook or with a computer, including labels, scales, units, dependent, and independent variables.

7. Know how to make comparisons: are two measured quantities equal? Is a measured quantity statistically equivalent to a theoretical value?

8. Use a computer to collect and analyze data.

Introduction

Waves can be broadly categorized as *longitudinal* or *transverse*. In a longitudinal wave, the displacement from equilibrium is parallel to the direction of propagation of the wave. Examples of longitudinal waves are sound waves and compression waves on a slinky. In a transverse wave, the displacement from equilibrium is perpendicular to the propagation direction; examples include water waves and waves on strings. Light, which is an electromagnetic wave, is transverse.

Consider light propagating parallel to the z-axis, i.e., out of the plane of this page. The associated electric and magnetic fields are perpendicular to each other and the propagation direction of the light, i.e., they point parallel to the plane of the page. Thus, the electric field is parallel to the x-y plane but it need not have any particular orientation in the x-y plane. If the electric fields along the light wave are randomly orientated in the x-y plane, the light is called *unpolarized*. If, however, the electric field has a fixed orientation, the light is said to be *linearly polarized*.

Unpolarized light sources are common but polarized light can be produced in various ways. You will investigate the production of polarized light by *scattering*, *reflection*, and *absorption*. In particular you will use polarizing filters to produce polarized light.

The first two parts of this lab introduce polarizing filters and explore polarization by absorption, scattering, and reflection and introduce a model of absorption and re-radiation by charged particles to explain the observations. The third part of this lab contains quantitative experiments involving light passing through successive polarizing filters.

Polarization is an important manifestation of the transverse nature of electromagnetic waves and is very important in the interaction of light with matter. Polarization has many technical applications such as polarizing sunglasses, non-destructive evaluation techniques, and liquid crystal displays such as flat panel monitors. While the electromagnetic and wave nature of light, along with the idea of re-radiation, is briefly touched upon in lecture, this lab is your main chance to explore the nature of the polarization of light.

Part I: Polarization by Absorption and Polarizing Filters

1. Turn on the lamp at the power strip. (For the set up with the smaller black lamp, also turn on the power at the grey box.) There should be two rectangular polarizing filters on your desk (white rectangular holder with a dark film inside). Using one of these polarizing filters, look at the lamp through the filter. Then, continue to look at the lamp through the filter while rotating it through 360° about an axis through its plane. Record your observations. Did you notice any dimming of the light?

2. Hold one polarizing filter in some fixed orientation. Hold a second polarizing filter in front of the first so that you are looking at the lamp through both filters. Rotate the second filter. What do you notice? Record your observations.

   A polarizing filter, or *polarizer*, transmits one component of the electric field (a vector) of an electromagnetic wave and absorbs the perpendicular component. The direction of the transmitted component, called the *transmission axis*, is determined by the structure of the polarizer material and is fixed with respect to the polarizer. The electromagnetic wave transmitted by a polarizer will only have an electric field component along the direction of the transmission axis. Light with this property is called *linearly polarized* and one refers to the direction of polarization (e.g., vertical or horizontal), meaning the direction of the associated electric field. Note that this is an idealization; in real materials, some of the light can pass through a set of polarizers with perpendicular trans-

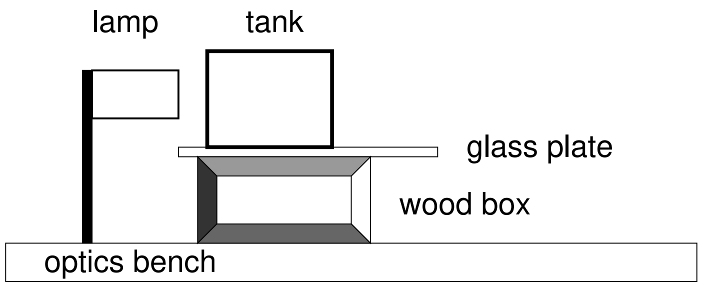


Figure 15.1: Setup for polarization by scattering and reflection. Be careful with the glass plate.

mission axes, and even when the electric field of the incident light is along the transmission axis, some light is absorbed.

3. In the two polarizer experiment, the light that emerges from the first polarizer is then polarized. Explain why the brightness of the light viewed through the second polarizer changes with the orientation of the second polarizer.

4. Briefly explain how you know that the light from the lamp is unpolarized. Why are polarizers also called filters?

Part II: Polarization by Scattering and Reflection

1. Fill the little plastic tank at your lab station about three quarters full with a mixture of water and creamer. This creamer is added to enhance the scattering of the light.

2. Confirm that your apparatus setup matches Figure 15.1, and make sure the reflective side of the glass plate facing up. Adjust the vertical height of the lamp so that the light beam goes through the tank.

3. Observe the **transmitted** light coming out of the tank opposite to the lamp. You should also notice scattered light coming out of the sides and top of the tank and reflected light in the glass plate. Using one of the (rectangular) polarizers, look at the **transmitted light** (from an angle if necessary). What happens to the intensity of the **transmitted** light as you rotate the polarizer? Is the transmitted light polarized or not?

4. Observe the light **scattered out of one side** of the tank through the polarizer. What happens to the intensity of the scattered light as you rotate the polarizer? Is this light polarized or not?

5. Repeat step 4 for the light **scattered out the top** of the tank.

6. We will explain these observations in terms of the directions of the electric fields

involved in the absorption and radiation of light by an accelerated charge.

Incident light on an atom exposes the electrons in the atom to the electromagnetic wave's oscillating electric and magnetic fields. The effect of the electric field is much larger than that of the magnetic field and dominates the interaction; thus, the magnetic field can be ignored for our purposes. The oscillating electric field of the incident light causes the electrons to oscillate along the direction of the electric field. Some of the light's energy is thus transferred to the oscillating charges.

In a process referred to as *radiation*, accelerated charges emit electromagnetic waves. Because oscillating electrons are accelerating, they will emit electromagnetic waves. This is illustrated in a video clip from a simulation located in the folder `PHYS 211_212\212Lab\Polarization of Light` on the desktop. Play the video "Radiating Charge Example" (use the setting "Sinusoidal") and watch how the white lines (electromagnetic waves) react when the electron moves. The energy given to the electrons can thus be transferred to the electromagnetic field as emitted light. The electrons emit light in all directions except along the axis of their motion. The electric field is perpendicular to the direction of propagation and along the line in which the charge oscillates.

Re-radiation refers to the combined process, in which the electric field of the incident light sets the constituent electrons in the material into oscillation. The oscillating electrons then emit electromagnetic waves whose electric field strength and direction depend on those of the incident light and the direction of propagation.

7. Explain the polarization of the transmitted and scattered light from the water in terms of this re-radiation model, assuming that the lamp emits unpolarized light. Could the electric field of the scattered light have a component in the direction of the beam passing through the tank?

8. Use your observations from steps 4 and 7 to determine the transmission axis of the rectangular polarizer relative to its long or short edge. Determine the polarization of light from the computer screen. Determine the transmission axis of polarizing sunglasses.

9. On the side of the tank where the beam exits, you should see the exiting beam as an approximately circular glowing spot. You have previously ascertained that the light in the exiting beam is unpolarized. Now, again using your polarizing filter, observe the reflection of this glowing spot from the glass plate on which the tank rests. Position yourself at a viewing angle of approximately 30° above the horizontal (taller people will need to stand further away and shorter people will need to stand closer to the tank). What happens to the intensity of the reflected image of the beam as you rotate the filter? You may also look at the

reflections of the overhead lights on the floor. Is the reflected light polarized?

STOP

Discuss your observations and explanations of polarization by scattering and reflection with your instructor or TA.

Part III: Quantitative Observation of Polarization

You will now transmit light through successive adjustable polarizing filters and measure its intensity using an electronic detector. The detector, a Gallium Arsenide photodiode, produces an electrical current proportional to the light intensity. A circuit converts this to a voltage, measured by a digital voltmeter (DVM), which is proportional to the intensity of the light incident on the detector.

The transmitted intensity can be measured as a function of the orientation angle of one polarizer and compared to predictions obtained using electromagnetic waves.

Calibration

1. Remove the water tank from the optics bench. Attach the lamp to one end of the optics bench so that it illuminates the opening of the photodiode detector (small metal black box). Calibrate the light intensity with both polarizers #1 and #2 in place, as in Figure 15.2. Set the DVM to the `DCV 2V` scale. Rotate polarizer #2 until the voltage reading gives maximal voltage. Then adjust the light source to get a maximal reading of about 1.4V (below 1.5V). You can adjust the light intensity, in case you have the set-up with the big metallic light by pulling the light in or out (focus/defocus the beam); in case you have the set-up with the black smaller light, move the light closer or further away from the detector. Adjust the light intensity by moving the lamp and/or adjusting its focus until the reading is between 1 and 1.5V. These elements must remain fixed.

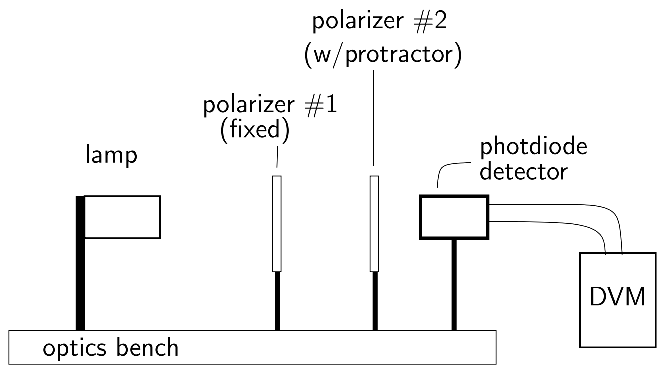


Figure 15.2: Setup for the two-polarizer measurement.

Two-Filter Experiment

2. Your goal is to measure (using the DVM) and plot (using Logger *Pro*) the light intensity as a function of the angle of the transmission axis of polarizer #2.

3. Open the Logger *Pro* program by navigating to the `PHYS211_212 Lab` folder and opening the folder `Polarization of Light`. Double-click on the file `polarization.cmbl`.

4. The experiment window provides a three-column spreadsheet and a graph window. The spreadsheet has columns for `Angle`, `Voltage`, and `Radians`. The `Angle` column displays the angles of polarizer #2 between 0° to 360° in 10° steps; the `Radians` column should simply be the radian conversion of the polarizer angles. As data is entered into the `Voltage` column it is plotted in the graph window.

5. Rotate polarizer #2 through angles in the range of 0° to 360° (in steps of 10°), and record the detector voltage for each angle in the appropriate cell. (The filter may slip, so you'll probably want to hold it at a particular angle as you are taking the reading.)

Classical Predictions for Two Filters

Any light transmitted by polarizer #1 is polarized in a direction parallel to the transmission axis of that polarizer. The intensity of light that passes through polarizer #2 is then related to the angle between the transmission axes of the two polarizers.

Consider only the light that is successfully transmitted by polarizer #1. The intensity of this light is reduced by a factor of $\cos^2 \Delta\theta_{12}$ as it passes through polarizer #2 where $\Delta\theta_{12} = \theta_2 - \theta_1$, and θ_1 and θ_2 are the angles at which the two polarizer transmission axes are oriented. Thus if I_0 is the intensity of the light that passes through polarizer #1, then the intensity of light after passing through polarizer #2 is

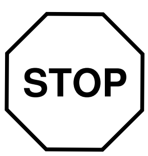
$$I = I_0 \cos^2(\theta_2 - \theta_1) = I_0 \cos^2 \Delta\theta_{12}. \tag{15.1}$$

6. To compare the theory to your observations and to determine some of the parameters in Eq. (15.1) perform a manual curve fit as follows:

   - Note that the vertical scale on your graph is from 0 to 1.5 V. Your data might have its maximum at a lower value than 1.5 V. The easiest way to re-scale your graph is to click on the 1.5 and enter in a number slightly above your largest voltage reading.
   - Choose `Curve Fit` from the `Analyze` menu.
   - In the `Curve Fit` window, click `Define Function...` and enter the equation

     `A*(cos(B*x-C))^2 + D` (15.2)

     in the `Define Function` box and then click `OK` to return to the `Curve Fit` window.
   - Adjust the values of A, B, C and D using the parameter buttons to give the best fit to your data, i.e., minimize the value in the `RMSE Error` box. You should easily be able to estimate values for A and D from your graph and possibly even obtain good first guesses for B and/or C.



Before printing out your graph, show it to your instructor or TA.

7. Record A, B, C and D for your best fit and print your graph.
8. To what term in Eq. (15.1) does A in Eq. (15.2) correspond? To what does C correspond? What does Eq. (15.1) predict for the values of B and D?
9. Compare the numerical values for B and C from your manual curve fit to those predicted by Eq. (15.1). Based on step 1, what would you expect for A and how does this compare to the value produced by the curve fit? Explain any discrepancies. Repeat this for parameter D.

Three-Filter Experiment

1. Arrange the polarizing filters as in Figure 15.3, **without polarizer #2**. Adjust the angle of polarizer #3 until the detector voltage is a minimum. This guarantees that the transmission axes of polarizers #1 and #3 are perpendicular. **Do not change these once you have set them.**

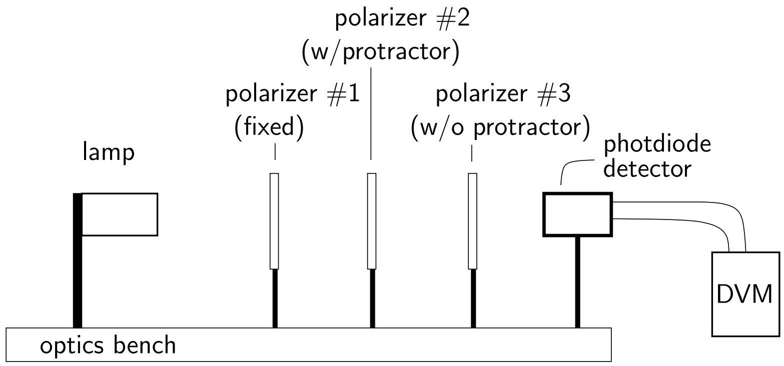


Figure 15.3: Setup for the three-polarizer measurement. Make sure that the transmission axes of Polarizer #1 and Polarizer #3 are perpendicular.

2. You may wonder what the point of inserting polarizer #2 is, if polarizers #1 and #3 are oriented with their transmission axes perpendicular to each other so that together they transmit no light. Explain why inserting polarizer #2 could result in transmission of light to the detector.

3. Insert polarizer #2, to which the protractor is attached, as illustrated in Figure 15.3. Rotate the polarizer so that the intensity of light at the detector is a **maximum** and record the voltage and the angle at this point. **Redefine this angle as zero** and rotate polarizer #2 from 0° to 360° (in terms of the new 0° mark), recording the voltage every 10°. Enter your data into the Logger *Pro* program. **Warning**: this will overwrite your old data.

4. Do a `Curve Fit` using Eq. (15.2). Show your best fit graph and values for A, B, C, and D to your instructor or TA and after approval, record them and print the graph.

Classical Predictions for Three Filters

5. Compare and contrast your graphs for two filters and three filters. The difference in intensity might not surprise you considering the additional filter. In what other respect are the two graphs very different?

6. Equation (15.1) implies that for two polarizers whose transmission axes are separated by angle $\Delta\theta_{12} = \theta_2 - \theta_1$, the intensity of light is reduced by a factor of $\cos^2 \Delta\theta_{12}$, as it passes through polarizer #2. Repeating this for transmission after polarizer #2 and through polarizer #3 gives

$$I = I_0 \cos^2(\theta_3 - \theta_2) \cos^2(\theta_2 - \theta_1), \tag{15.3}$$

where I_0 is the intensity of light transmitted by polarizer #1. Convince yourself and your partner that this is true.

In your experiment, polarizers #1 and #3 are oriented so that $\theta_3 = \theta_1 - \pi/2$. Using trigonometric identities, a more compact result is obtained:

$$\begin{aligned} I &= I_0 \cos^2(\theta_1 - \pi/2 - \theta_2)\cos^2(\theta_2 - \theta_1) \\ &= I_0 \sin^2(\theta_1 - \theta_2)\cos^2(\theta_2 - \theta_1) \\ &= \frac{I_0}{4}\sin^2[2(\theta_2 - \theta_1)] \\ &= \frac{I_0}{4}\cos^2[2(\theta_2 - \theta_1) - \pi/2]\,. \end{aligned} \tag{15.4}$$

Note that Eq. (15.4) is a special case of the more general Eq. (15.3) when applied to three polarizers where the transmission axes of the first and last polarizers are perpendicular.

7. What does Eq. (15.4) predict for the value of B? Compare the numerical value for B from your manual curve fit to this. Explain these striking differences between the two polarizer and the three polarizer case using a physical argument.

STOP

Discuss your results about two and three polarizers with your instructor or TA.