Lab 10: Polarization

What’s this lab about?
In this lab you investigate effects arising when using polarized light.
There are four parts to the lab:
PART A
- Use a polarizer to explore common occurrences of polarized light
PART B
- Use a polariscope to understand how polarized light waves can be superposed, or decomposed into components.
PART C
- Create and investigate circular polarization.
PART D
- Use the ideas of circular polarization and superposition to see how polarized light interacts with biological sugar molecules.

Why are we doing this?
Understanding polarized light is important applications such as microscopy, as well as in understanding the properties of electromagnetic waves.

What should I be thinking about before I start this lab?
Suppose an electromagnetic wave is propagating through your area at the speed of light.
If you could take a snapshot, you could freeze the electric and magnetic fields at a particular instant in time so that you could look at them. At each point in space around you, and at each instant in time, you would see electric and magnetic fields with these properties:

i) $\bar{E}$ and $\bar{B}$ are always perpendicular to each other, and also to the wave propagation direction (such that $\bar{E} \times \bar{B}$ is in the propagation direction)

ii) The magnitudes $|\bar{E}| = E$ and $|\bar{B}| = B$ are related as $B(x_o, y_o, z_o, t_o) = \left(1/c\right)E(x_o, y_o, z_o, t_o)$.

iii) $\bar{E}$ and $\bar{B}$ both oscillate in time with a frequency $f = v/\lambda$ (v is the propagation speed)

iv) It takes a time $T = 1/f$ (the period) for the fields to complete one complete cycle at a fixed point in space, and a distance $\lambda$ (the wavelength) to complete one complete cycle at a fixed time.
A. Making and detecting polarized electromagnetic waves

In a linearly polarized electromagnetic wave, the electric field varies in time and space, but it always lies in a plane of polarization. Since the associated magnetic field is always perpendicular to this, we can describe the polarization completely by describing the orientation of the electric field.

Light doesn’t often look like this unless it is specially prepared. It is usually a superposition of all possible polarizations, which we call unpolarized light.

A linear polarizer can be used to investigate the polarization state. It completely transmits linearly polarized light aligned with its transmission axis, and completely absorbs light linearly polarized perpendicular to its transmission axis.

I. Polarization by reflection.

Light is partially polarized whenever it is reflected. You can check this by using the linear polarizer from the polarization kit on the lab table. Raised lines on the black plastic disc that holds the polarizing material mark the transmission axis.

i) First look through the polarizer directly at the black desklamp on your lab bench. Does the desklamp produce polarized light? How did you tell?

ii) Now aim the lamp at the lab bench at about a 30° to 45° angle (from the horizontal), and look through the polarizer at the reflection of the bulb. Is this light polarized? In what direction is the plane of polarization?

iii) Polaroid sunglasses operate on the same principle as your kit polarizer. In what direction is the transmission axis of Polaroid sunglasses? Explain.

iv) Use your polarizer to look at your cell-phone display or a computer LCD monitor. Describe the light emitted by these.
The polariscope

Your polariscope has two polarizers (even though one is called an analyzer!):

The bottom one sits directly over the (unpolarized) incandescent bulb, and is fixed in place. In a two-polarizer system, it is usually called the “polarizer”, since it produces linear polarized light from an unpolarized source.

The top one can rotate. It is usually in-line with the bottom polarizer, but can also be swung to the side. In a two-polarizer system, it is usually called the “analyser”, since it analyzes whether a sample placed above the bottom polarizer has altered the polarization.

1. Turn on your polariscope and look down into the top polarizer. Describe the intensity variations while rotating the top polarizer through 360°.

2. Find the transmission axis of the bottom polarizer with the small polarizer (mounted in a black plastic ring) from your box. This one has its transmission axis marked with two ridges in the plastic. Explain your procedure and use a piece of masking tape to mark it on the rim of the polariscope.

Find the transmission axis of the top polarizer and mark it also.

3. What angle is between the transmission axes of the two polarizers when there is: Maximum transmission?

What about no transmission?
B. Transmission through a polarizer:
In the previous section, you found that a linear polarizer will transmit a light wave whose electric field vector is parallel to the transmission axis, and blocks (absorbs) one with electric field vector perpendicular to that direction. For angles not 0° or 90° with respect to the transmission axis, the polarizer transmits the component of the E-field along the transmission axis and absorbs the rest.

B1. Set the analyzer on your polariscope so that no light is transmitted. Now insert the small round polarizer from your kit between them and rotate it.

Why does light now get through at some angles?

B2. Rotate the middle polarizer through a full 360°. From your experimental observations, qualitatively sketch the intensity through the top analyzer vs angle of the middle polarizer transmission axis relative to the transmission axis of the bottom fixed polarizer.

B3. At what angles of the inner polarizer do you get maximum intensity? Explain.
C. Circular Polarization:
An important type of polarization occurs when two plane-polarized waves are added together. One wave is time-delayed by one quarter of a period (a 90° phase shift). In the figure the horizontal EM wave starts later in time. (Only the E-fields of the two EM waves are shown).

I. The graphs below show the E-fields of the two linearly-polarized waves at time intervals $\Delta t=T/8$ ($T$ is the wave period). The wave polarized along the $x$-axis starts later in time. Draw the vector sum of the two E-fields on each plot.
2. Describe the time-dependence of the total E-field (direction and magnitude). Does the magnitude change in time? Does the direction change in time?

When the horizontal component starts \( \frac{1}{4} \) period earlier (\(-90^\circ\) phase shift) rather than later, the electric field vector rotates in the opposite direction. These two polarization states are **right and left circular**.

**Making circularly polarized light**

As you showed above, you can make circularly polarized light by combining two linearly polarized waves, with their plane of polarizations at right angles, and with a relative delay of \( \frac{1}{4} \) wavelength.

There is a very easy way to do this. Some materials are optically anisotropic, meaning that light waves polarized along different directions travel at different speeds. This means that the slower one is delayed relative to the faster one. You have two of these in your plastic box. The thickness of the plate is such that the time delay is \( \frac{1}{4} \) of the wave oscillation period \( T \) (equivalent to a \( \frac{1}{4} \) wavelength delay, or \( 90^\circ \) in phase). These are called \( \frac{1}{4} \)-wave plates.

3. You have \( \frac{1}{4} \) wave plate in your kit made from quartz. It gives exactly \( \frac{1}{4} \) wavelength delay between the fast and slow axes for 540 nm wavelength light. The index of refraction along the slow axis is \( n_{\text{slow}} = 1.5 \), and along the fast axis is \( n_{\text{fast}} = 1.4955 \)

a) What is the propagation speed?

i) along the slow axis?

ii) along the fast axis?

b) How thick must the plate be so that the wave along the slow axis takes \( T/4 \) seconds longer to make it through the waveplate than the wave along the fast axis? Here \( T \) is the oscillation period of 540 nm light in vacuum.

[Hint: if the waveplate thickness is \( L \), how many seconds does it take for the slow wave to travel through the waveplate? The fast wave?]
Analyzing circular polarization:

Set the ¼ wave plate on the lower polarizer of the polariscope. Align the wave plate so that the linearly polarized light enters with its plane of polarization halfway between the fast and slow axes of the ¼ wave plate. (The fast axis is marked on the brass holder)

Now x- and y-components of the linearly polarized light have equal amplitude, and are aligned with the fast and slow axes of the ¼ wave plate.

4. Explain why this should produce circularly-polarized light.

5. Now rotate the top polarizer. The intensity of the light transmitted through the wave plate remains approximately constant as you rotate the analyzer (top polarizer) [you may need to slightly adjust the wave-plate angle]. Explain why this happens.
D. Chiral molecules and polarized light

We discuss circular polarization because many molecules interact differently with left-handed and right-handed light due to their molecular “chirality”, or “handedness”. Amino acids (shown at right in both chiralities) and sugars are chiral. Your body uses and produces only D-sugars (right-handed) and only L-amino acids (left-handed).

1. Explain why the molecules in the figure above are not identical.

In a biological (right-handed) sugar solution, right and left circularly polarized light interact differently with the right-handed molecules. The result is that the EM waves propagate at different speeds. To observe this, we could have a race between right- and left-circularly polarized light. We would start them at the same time, and see which one arrived first at the other end of the sugar solution. Sounds complicated, but it turns out that right- and left-circularly polarized light together is something you’ve seen before:

2. Below are plots that let you superimpose two EM waves with right and left circular polarizations. At $t_0$, both have their E-fields pointing along the y-axis (i.e. they are ‘in phase’ with each other). As time progresses, one rotates clockwise and the other counter-clockwise. Add the E-fields as vectors as you did the two linear polarizations in C1. Draw the resultant vector at each time step.

Describe the polarization of the EM wave that is the sum of these two circularly polarized waves. Is it circularly polarized? Linearly polarized? How does the electric field point?
This means that you can race right- and left- circularly polarized light through a chiral solution by sending in linearly polarized light. In D2 above, the right and left-circularly polarized light start together (in-phase), ready to race.

But they propagate at different speeds, so that one will arrive sooner at the other end. This results in a relative delay between right- and left- circular polarization when they leave the chiral solution.

3. Below are plots that let you superimpose the electric field vectors of right and left circularly polarized EM waves with a relative delay. The left-handed light is delayed \((\phi_{\text{left}} - \phi_{\text{right}}) = 90^\circ\) (1/4 period) from the right-handed light. Add the E-fields as vectors as you did in D2. Draw the resultant vector at each time step.

\[
\theta_{\text{pol}} = \frac{\phi_{\text{left}} - \phi_{\text{right}}}{2}
\]

Describe the polarization of the sum of these two circularly polarized waves.

4. The relation between the polarization angle \(\theta\) of the resulting linear polarization, and the relative phase delay \(\phi_{\text{left}} - \phi_{\text{right}}\) between the left- and right-handed polarization components, is \(\theta_{\text{pol}} = (\phi_{\text{left}} - \phi_{\text{right}})/2\). Explain how this is consistent with the plots you made in D2 and D3.
Now you do the experiment, sending linearly polarized light through a concentrated biological sugar solution. We use Karo corn syrup because it is a very concentrated chiral solution of right-handed molecules (sugars) only. If you don’t know what Karo syrup is, call your mother and ask her. She probably hasn’t heard from you in a while, and would enjoy talking with you.

The right- and left-circularly polarized components of the linearly polarized light propagate at different speeds. They start at the same time, but arrive at the other end with a relative delay, which you just showed appears as rotated linearly polarized light.

Get a set of four jars of Karo syrup (three small and one large, with different heights of syrup). Don’t tip them: the syrup takes time to run back down into the jar.

5. Place the large jar (lid off, open end up) on the polarizer and rotate the analyzer while looking through the polarizers and syrup. You should see colors in the syrup. In what order do the colors appear as you rotate the analyzer clockwise?

Since the rotation appears to be different for different colors (wavelengths), place a color filter (colored transparency) under the syrup so you are only looking at “one color” (see spectral transmission below).

![Graphs showing transmission vs. wavelength for Roscolux #122 and #124 filters.]

Rotate the analyzer so the light outside the jar but through the filter is extinguished. Then rotate the analyzer until the light through the syrup is extinguished.

The difference of these angles is the angle by which the Karo has rotated the light.

6. What direction (clockwise or counter-clockwise, looking from the top) is the plane of polarization rotated? How did you tell? (Hint: a little bit of Karo rotates the polarization a little bit, and a lot rotates it more, so look at the jar with a little Karo).
Record the polarization rotation of the large jar for the red and green filters.
Filter color: Relative rotation (deg):

7. Do this for the other jars and record all your data below.

<table>
<thead>
<tr>
<th>Sugar depth</th>
<th>Green angle</th>
<th>Red angle</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

8. Plot the data for the two colors on the axes below.
Now you analyze the data, first using an approximate value for the velocity ratios in order to develop the concepts.

9. Suppose that the right-handed component moves at 0.999997 the speed of the left-handed component \( \frac{v_{\text{right}}}{v_{\text{left}}} = 0.999997 \). Then the left-handed component arrives at the top of the syrup a short time \( \Delta t \) before the right-handed component.

What is \( \Delta t \) after traversing 8 cm of Karo? (take \( v_{\text{left}} = \frac{c}{n_{\text{Karo}}} = \frac{3 \times 10^8 \text{ m/s}}{1.5} = 2 \times 10^8 \text{ m/s} \).)

The phase difference between the right- and left-handed components depends on the arrival time difference \( \Delta t \) and on the oscillation period \( T \). For instance \( \Delta t = T / 2 \) corresponds to a phase shift of \( \pi \) (180°). \( \Delta t = T / 4 \) gives a phase shift of \( \pi / 2 \) (90°).

10. The peak wavelength of red light you used above is about 660 nm in vacuum.
This has an oscillation period \( T = \frac{\lambda}{c} = 2.20 \times 10^{-15} \text{ s} \).
What is the phase difference \( \phi_{\text{left}} - \phi_{\text{right}} \) between the left- and right-handed components for the time delay \( \Delta t \) calculated in D9?

11. The peak wavelength of green light you used above is about 520 nm in vacuum.
This has an oscillation period of \( T = \frac{\lambda}{c} = 1.73 \times 10^{-15} \text{ s} \)
What is the phase difference \( \phi_{\text{left}} - \phi_{\text{right}} \) between the left- and right-handed components for the time delay \( \Delta t \) calculated in D9?

12. Using \( \theta_{\text{pol}} = \frac{\phi_{\text{left}} - \phi_{\text{right}}}{2} \) from D4, what polarization rotations are these?

Red Light rotation:

Green Light rotation:
13. Why did the same arrival time difference result in different polarization rotations for different colors of light?

14. Explain whether your answer to the question above describes the order of the colors you observed in D5, assuming that the arrival time delay does not depend on wavelength.

15. Now you use your measurements of rotation angle to determine the ratio of right- and left-handed polarization velocities in the right-handed sugar solution.
   i) Using your data for polarization rotation through 8 cm of Karo, calculate the difference in arrival time $\Delta t$ for the left- and right-handed components.

<table>
<thead>
<tr>
<th>Red light $\Delta t$</th>
<th>Green light $\Delta t$</th>
</tr>
</thead>
</table>

   ii) From D9-12, you should expect that $v_{right}$ is just a little smaller than $v_{left}$. Again taking $v_{left} = c/n_{Karo} = 2 \times 10^8 \text{m/s}$, determine $v_{right}/v_{left}$ from your $\Delta t$ in i) above.

<table>
<thead>
<tr>
<th>Red light $v_{right}/v_{left}$</th>
<th>Green light $v_{right}/v_{left}$</th>
</tr>
</thead>
</table>

   iii) Qualitatively, how did this extremely small speed difference show up as such a large polarization rotation?