5. Polarization

A. Objectives

- Experimentally verify Malus' law for a polarizer.
- Study light transmission through three polarizers.
- Measure the rotation of polarization by a half-wave plate.
- Observe an example of optical activity
- Measure Brewster's angle, and determine whether light is polarized by reflection.

B. Equipment required

1. Optical breadboard and beam stop to use as a screen
2. Platform with post mount
3. LED light source with power supply, 2 mm aperture, and mount
4. 100 mm focal length lens with 14 mm diameter aperture and mount
5. 50 mm focal length lens with mount
6. Pasco light sensor with mount
7. Three polarizers with rotation mounts
8. Half-wave plate with rotation mount
9. Glass slab
10. Protractor
11. 300 mm focal length lens in square mount

C. Introduction

Polarization

During the period 1860-1865, J.C. Maxwell discovered that "Maxwell's equations" have wave solutions. Such waves consist of the vibrations of electric and magnetic fields. One such solution is

$$\vec{E} = E_0 \hat{e} \cos\left(\omega t - kz + \phi_E\right) \tag{5.1}$$

$$\vec{B} = B_0 \hat{b} \cos\left(\omega t - kz + \phi_B\right) \tag{5.2}$$

where E_0 and B_0 are the amplitudes of the electric and magnetic field vibration, and $\hat{e}$ and $\hat{b}$ are unit vectors that point in the direction of the electric and magnetic field vectors, respectively. Maxwell's equations place additional restrictions on this solution (in vacuum) as follows:

- $\omega = ck,\ c = \dfrac{1}{\sqrt{\varepsilon_0 \mu_0}} =$ speed of light (5.3)
- The phases must be equal; $\phi_E = \phi_B$ (5.4)
- The ratio of electric and magnetic fields is fixed; in SI units $B_0 = E_0 / c$. (5.5)
- The unit vectors $\hat{e}, \hat{b},$ and $\hat{z}$ must be mutually perpendicular, such that $\hat{e} \times \hat{b} = \hat{z}$. (5.6)

This particular solution is an *electromagnetic plane wave* that propagates in the *z*-direction. (We are taking a propagation direction $\hat{k} \equiv \hat{z}$.)

Often, we focus our attention on the electric field $\vec{E}$ only. Part of the reason is that $\vec{B}$ does not contain any independent parameters, so it can be determined from $\vec{E}$. Also, the electric field often dominates interactions with matter. We'll restrict out attention to $\vec{E}$ for the rest of this lab.

The unit vector $\hat{e}$ is called the *polarization vector*. It is a unit vector that points in the direction of vibration of the electric field. Condition (5.6) says that $\hat{e}$ has to be perpendicular to $\hat{z}$, but otherwise places no restriction on it. So, $\hat{e}$ must lie in the *x*-*y* plane. Two solutions that work are

Solution 1: $\vec{E}_1 = E_{01}\hat{e}_1 \cos\left(\omega t - kz + \phi_{01}\right) = E_{01}\hat{x}\cos\left(\omega t - kz + \phi_{01}\right)$ (5.7)

Solution 2: $\vec{E}_2 = E_{02}\hat{e}_2 \cos\left(\omega t - kz + \phi_{02}\right) = E_{02}\hat{y}\cos\left(\omega t - kz + \phi_{02}\right)$ (5.8)

Solution 1 has a polarization vector $\hat{e}_1 = \hat{x}$, and solution 2 has a polarization vector $\hat{e}_2 = \hat{y}$. We have chosen these two vectors to be orthogonal, so that *any* polarization vector $\hat{e}$ can be written as a linear combination of $\hat{e}_1$ and $\hat{e}_2$. Such orthogonal unit vectors are called *polarization basis vectors.*

Maxwell's equations obey superposition, so any linear combination of $\vec{E}_1$ and $\vec{E}_2$ is also a solution to Maxwell's equation, for instance:

$$\vec{E} = E_{01}\hat{x}\cos\left(\omega t - kz + \phi_{01}\right) + E_{02}\hat{y}\cos\left(\omega t - kz + \phi_{02}\right) \tag{5.9}$$

Equation (5.9) gives the most general solution of Maxwell's equations that has propagation direction $\hat{k} \equiv \hat{z}$ and frequency exactly equal to ω. It contains four free parameters: $E_{01}, E_{02}, \phi_{01},$ and ϕ_{02}. It describes a linear superposition of vibrations of $\vec{E}$ along the $\hat{x}$ and $\hat{y}$ directions. The *polarization* of the electromagnetic wave describes the path of the vibration of $\vec{E}$ in the *x*-*y* plane.

Linear polarization

Suppose that $\phi_{01} = \phi_{02} \equiv \phi_0$. In this case, we have

$$\vec{E} = \left(E_{01}\hat{x} + E_{02}\hat{y}\right)\cos\left(\omega t - kz + \phi_0\right) \tag{5.10}$$

This case is referred to as *linear polarization.* If we wish, we can rewrite this in the form

$$\vec{E} = \left(E_0\hat{e}\right)\cos\left(\omega t - kz + \phi_0\right) \tag{5.11}$$

where

$$E_0 = \sqrt{E_{01}{}^2 + E_{02}{}^2} \tag{5.12}$$

and

$$\hat{e} = \frac{E_{01}}{E_0}\hat{x} + \frac{E_{02}}{E_0}\hat{y} \tag{5.13}$$

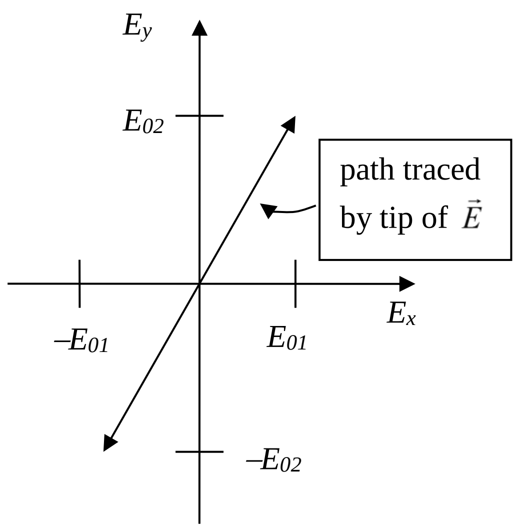

Figure 5.1. Vibration of the electric field vector for a linearly polarized wave.

The electric field vector vibrates in the $\hat{e}$-direction with amplitude E_0. If we plot the path traced out by the tip of the vector $\vec{E}$ vs. time in the E_x-E_y plane at any fixed position, it traces out a straight line, as shown in Figure 5.1.

Circular polarization

Suppose that $\phi_{01} = \phi_0$, $\phi_{01} = \phi_0 \mp \pi/2$, and $E_{01} = E_{02}$. Then

$$\vec{E} = \frac{E_0}{\sqrt{2}}\left(\hat{x}\cos\left(\omega t - kz + \phi_0\right) + \hat{y}\cos\left(\omega t - kz + \phi_0 \mp \frac{\pi}{2}\right)\right), \text{ or}$$

$$\vec{E} = \frac{E_0}{\sqrt{2}}\left(\hat{x}\cos\left(\omega t - kz + \phi_0\right) \pm \hat{y}\sin\left(\omega t - kz + \phi_0\right)\right) \tag{5.14}$$

This case is called *circular polarization.* If we plot the path traced out by the tip of the vector $\vec{E}$ *vs*. time in the *x*-*y* plane at any fixed position, it traces out a circle, as illustrated in Figure 5.2.

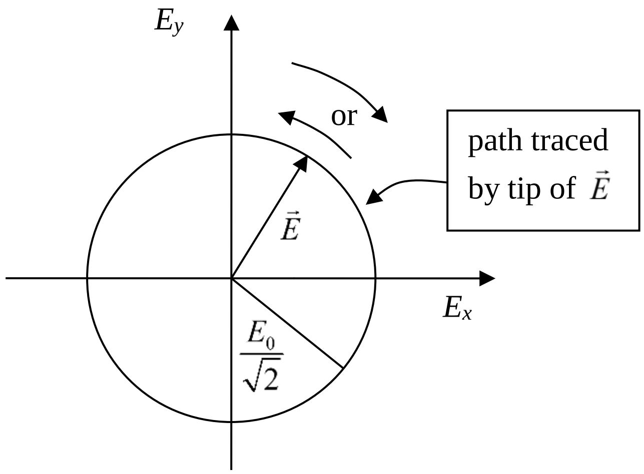

Figure 5.2. Vibration of the electric field vector for a circularly polarized wave.

There are two possible directions of rotation of the $\vec{E}$-field vector, which are called *left circular polarization* and *right circular polarization.* To determine which is which, imagine that you look toward the source of light, and that you can see the electric field vector at some fixed point in space. If that vector rotates clockwise, the wave is right circularly polarized. If that vector rotates counter-clockwise, the wave is left circularly polarized.

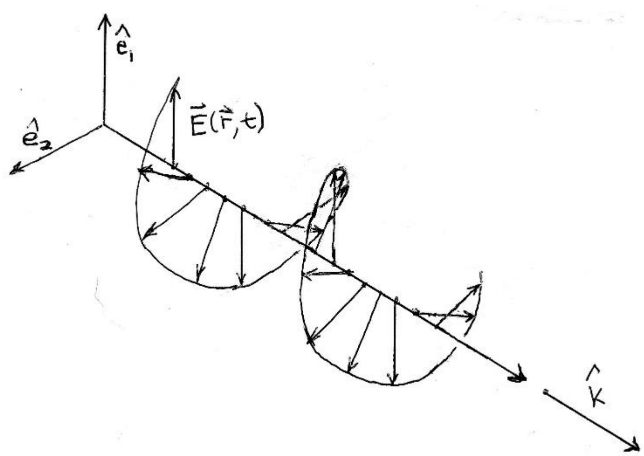

Figure 5.3. Electric field vector vs. position along a line in the direction of propagation at a fixed time, for a right-circularly polarized wave.

Another way to visualize a circularly polarized wave is to show the electric field vector as a function of position along the propagation direction at some fixed time. This is shown in Figure

5.3 for a *right* circularly polarized wave. (As time moves forward, this set of vectors translates in the $+\hat{k}$-direction, so $\vec{E}$ at any fixed position rotates *clockwise* as viewed from the $+\hat{k}$ direction.)

Elliptical polarization

If we choose arbitrary values for $E_{01}, E_{02}, \phi_{01},$ and ϕ_{02}, we'll typically have neither linear nor circular polarization. This is the general case given in equation (5.9), and is referred to as *elliptical polarization*. If we plot the path traced out by the tip of the vector $\vec{E}$ vs. time in the E_x-E_y plane at any fixed position, it traces out an ellipse, as shown in Figure 5.4. There are two possible directions of rotation of the field vector around the ellipse. These are referred to as "right" or "left" elliptical polarization according to the same convention used for circular polarization.

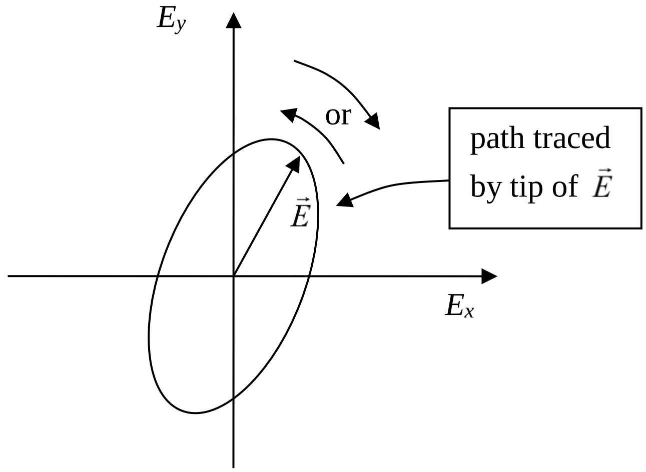

Figure 5.4. Vibration of the electric field vector for an elliptically polarized wave.

Unpolarized and partially polarized radiation

Natural light is often *unpolarized*. This means that the direction of vibration of $\vec{E}$ fluctuates randomly in time, so that on average it has no net orientation or handedness. This occurs whenever the source of radiation is composed of radiators that have no net orientation or handedness. The sun and incandescent light bulbs emit unpolarized light.

Unpolarized light cannot be described by equation (5.9). This equation has a fixed polarization, not a fluctuating one. Also, unpolarized light must have random fluctuations of its electric field. Such a field cannot be described by a sine wave function of a single frequency ω. It must contain a spread of frequencies. We won't cover the mathematical description of unpolarized light here.

In some cases light is *partially polarized*. This is light which does not have one of the "pure" polarization states described by equation (5.9). But it is not completely randomly polarized either. For partially polarized light, the direction of $\vec{E}$ fluctuates randomly in time and in space, but in such a way that there is still some net average orientation or handedness to its vibration. Partially polarized light often occurs when natural light is scattered or reflected. For instance, light from a blue sky is partially polarized, because it is sunlight that has been scattered by air molecules. Glints of sunlight from a car are partially polarized because they are sunlight that has been reflected from the car's surface.

Polarizers

Linearly polarized radiation can be produced with *polarizers*. For microwaves and infrared radiation, the *wire-grid polarizer*, shown in Figure 5.5, can be used. This polarizer consists of a set of parallel metal wires. When an electromagnetic wave hits the polarizer, the component of the field that is parallel to the wires drives an oscillating current in them. Energy is dissipated due to the electrical resistance of the wires, and this absorbs a lot of the energy from the polarization component parallel to the wire. Also, to this polarization component the wires don't look so different from a continuous metal surface, so much of the light in that polarization is reflected. On the other hand, the polarization component perpendicular to the wires does not drive much current since there is no conduction pathway in that direction. Therefore very little energy is absorbed or reflected from that polarization component. So the electromagnetic wave emerges linearly polarized in the direction perpendicular to the wires.

For the wire grid polarizer to work well, the spacing between the wires should be small compared to a wavelength. It's not practical to make a polarizer for visible light this way, but versions of the wire grid polarizer can be made for infrared wavelengths as short as 2 microns.

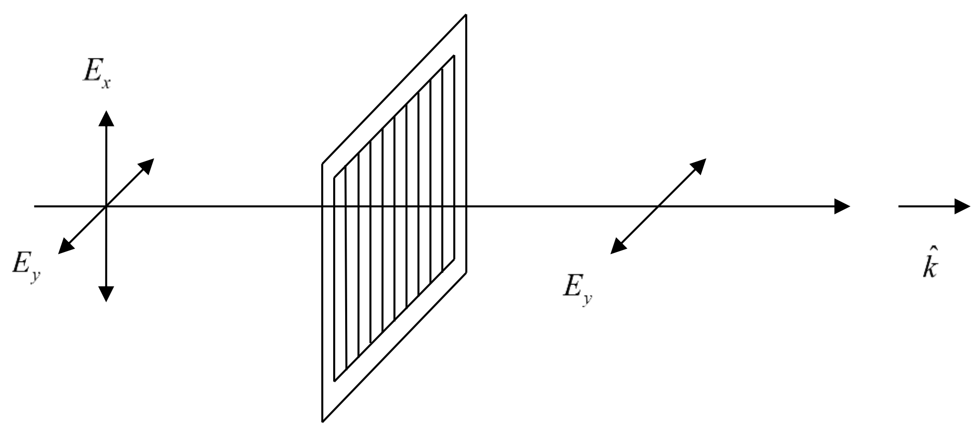

Figure 5.5. Wire grid polarizer.

Some materials exhibit the property of *dichroism*, the preferential absorption of one polarization component. At a microscopic level, the principle is the same as the wire grid polarizer. Dichroic materials contain oriented doped polymers, elongated metal nanocrystals, or other molecules or crystals that can conduct an electric current preferentially in one direction. Electrical conduction in the perpendicular direction is suppressed. The resulting structure is essentially a microscopic version of the wire grid polarizer. Films made of these materials have been sold for many years as “Polaroid” film. This is also what’s on “glare blocking” sunglasses, if you have them. This is the type of polarizer we'll use in this lab.

Other types of polarizer work through mechanisms other than dichroism, but I won't discuss these here.

Malus’ Law

Suppose that an electromagnetic wave propagates in the $+\hat{z}$ direction and passes through two polarizers in sequence, as shown in Figure 5.6. Suppose that the polarizers are ideal, i.e. that they transmit 100% of the field amplitude along one polarization direction (indicated by the double arrow) and completely block the other polarization component. Finally suppose that the transmission axis of the first polarizer is set to the $\hat{x}$ direction, and that the transmission axis of the second polarizer is set to an angle θ with respect to the first. Let $\vec{E}_i$ and I_i be the electromagnetic field and intensity between the two polarizers, and $\vec{E}_t$ and I_t be the field and intensity after the second polarizer.

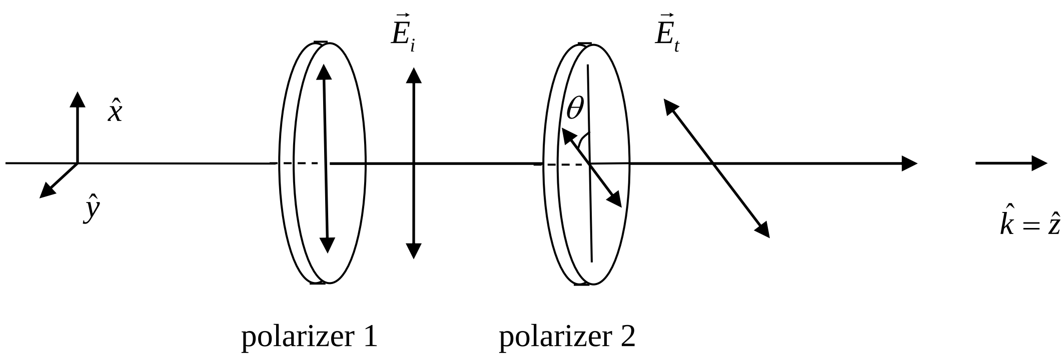

Figure 5.6. Illustration of polarizations for Malus’ law.

Question: What fraction of the intensity I_i is transmitted through polarizer 2?

Answer: We are free to choose any two perpendicular unit vectors in the *x*-*y* plane to serve as polarization basis vectors. Let’s choose $\hat{e}_1 = \cos(\theta)\hat{x} + \sin(\theta)\hat{y}$ and $\hat{e}_2 = \sin(\theta)\hat{x} - \cos(\theta)\hat{y}$. It follows that we can write $\hat{x} = \cos(\theta)\hat{e}_1 + \sin(\theta)\hat{e}_2$. Also

$$\vec{E}_i = E_{0i}\hat{x}\cos(\omega t - kz + \phi_i) = E_{0i}\left(\cos(\theta)\hat{e}_1 + \sin(\theta)\hat{e}_2\right)\cos(\omega t - kz + \phi_i) \tag{5.15}$$

$\hat{e}_1$ coincides with the transmission axis of polarizer 2. Therefore the component of $\vec{E}_i$ along $\hat{e}_1$ is transmitted through polarizer 2 with no loss, whereas the component of $\vec{E}_i$ along $\hat{e}_2$ is completely blocked. So the field after polarizer 2 is

$$\vec{E}_t = E_{0t}\hat{e}_1\cos(\omega t - kz + \phi_t) = E_{0i}\cos(\theta)\hat{e}_1\cos(\omega t - kz + \phi_t) \tag{5.16}$$

It turns out that the time-averaged intensity of the electromagnetic wave given by equation (5.9) is

$$I = \frac{1}{2}\varepsilon_0 c E_{01}{}^2 + \frac{1}{2}\varepsilon_0 c E_{02}{}^2 = \frac{1}{2}\varepsilon_0 c E_0{}^2 \tag{5.17}$$

where *c* is the speed of light, and $\varepsilon_0 = 8.854\times10^{-12}$ F/m is the electric constant. It follows that the intensity transmitted through polarizer 2 is $I_t = \frac{1}{2}\varepsilon_0 c E_{0t}{}^2 = \frac{1}{2}\varepsilon_0 c E_{0i}{}^2 \cos^2(\theta)$, and since

$I_i = \frac{1}{2}\varepsilon_0 c E_{0i}{}^2$, that

$$I_t = I_i \cos^2(\theta) \tag{5.18}$$

A fraction $\cos^2(\theta)$ *of the power is transmitted through the polarizer*. This result is known as *Malus' Law.*

This arrangement of two polarizers with an adjustable relative angle provides a nice way to make an adjustable attenuator for laser beams in the laboratory. (We used this already in Experiment 3.) The intensity is theoretically zero if $\theta = 90°$. However, in any real polarizer the transmitted intensity will be small and non-zero even for $\theta = 90°$. A useful measure of the quality of a polarizer is its *extinction ratio*. This is the ratio of the intensity transmitted through a pair of identical polarizers with $\theta = 0^0$ to the intensity transmitted with $\theta = 90°$. Extinction ratios of polarizers mostly lie in the range from 10^2 to 10^5. Certain very expensive polarizers, when used carefully, can have extinction ratios as high as 10^7.

Waveplates

The speed of light in a transparent material is less than the speed of light in vacuum. This effect is called *refraction.* The *index of refraction n* is the factor by which the speed is reduced, *i.e.* the speed of light in the material is $\mathrm{v} = \frac{c}{n}$.

A material that has an index of refraction that depends on polarization is said to be *birefringent.* This occurs because the material's bound electrons vibrate more strongly in response to an electric field of one polarization than in response to another polarization. Microscopically, this occurs because of some asymmetry in the electronic structure of the material. In birefringent crystals, this arises from the asymmetry of the arrangement of atoms in the crystal. In polymer films, this occurs because the polymer molecules tend to lie parallel to each other, so there is an asymmetry in the structure between the direction parallel to the polymers and the direction perpendicular to the polymers. This is similar to what happens in polarizers based on dichroic polymers, except that it is an effect of refraction rather than absorption. *Stress birefrigence* occurs when a material is stressed; in this case the asymmetry arises from the compression of the material along the direction of the applied stress.

Waveplates are thin plates of transparent birefringent material, cut in such a way that there are two special axes in the plane of the plate that are perpendicular to each other: the *fast axis* and the *slow axis*. If light shining through the plate is linearly polarized parallel to the fast axis, it will experience one index of refraction n_f. Light with polarization parallel to the slow axis will experience a different index of refraction n_s. The indices satisfy the inequality $n_f < n_s$. Figure 5.7 illustrates a linearly polarized wave that is transmitted through a waveplate of thickness *b*, with a fast axis that is tilted at an angle θ with respect to the polarization of the incident wave.

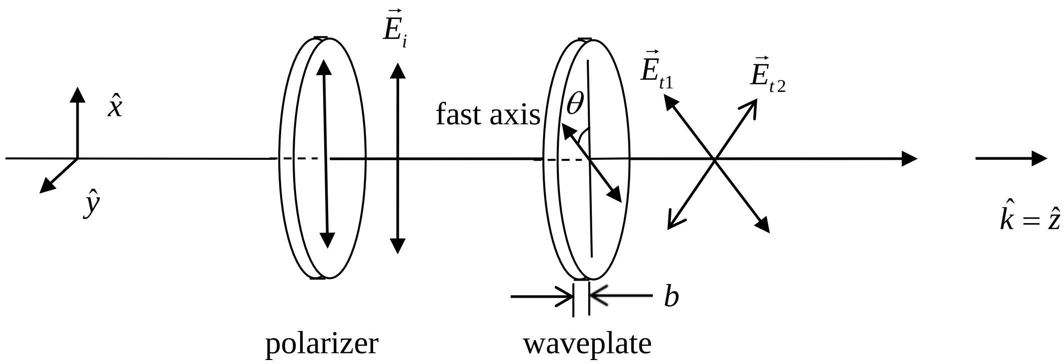

Figure 5.7. Linearly polarized wave transmitted through a waveplate.

Question: What is electric field of the wave after the waveplate?

Answer: Let's take the $\hat{x}$-direction to be the polarization direction of the incident wave. So before the waveplate, the electric field of the wave is $\vec{E}_i = E_0 \hat{x} \cos(\omega t - kz)$. It is easiest to analyze what happens if we re-express the incident wave as

$$\vec{E}_i = E_0 \hat{x} \cos(\omega t - kz) = \vec{E}_{i1} + \vec{E}_{i2} = E_0 \cos\theta \hat{e}_1 \cos(\omega t - kz) + E_0 \sin\theta \hat{e}_2 \cos(\omega t - kz) \quad (5.19)$$

where $\hat{e}_1$ is a unit vector pointing in the direction of the fast axis, and $\hat{e}_2$ is a unit vector pointing in the direction of the slow axis. That is, we express the original polarization vector $\hat{x}$ in terms of its components in the basis $\{\hat{e}_1, \hat{e}_1\}$ of vectors that specify the waveplate axes.

Next, we analyze separately what happens to the incident wave components $\vec{E}_{i1}$ and $\vec{E}_{i2}$. The waveplate is transparent, so both components pass through the plate with no loss of intensity, and the amplitudes of the two waves are the same after the plate as before the plate: $E_0 \cos\theta$ and $E_0 \sin\theta$. However, wave $\vec{E}_{i1}$ does experience an index of refraction n_f as it passes through the plate. This causes the phase of the wave exiting the plate to differ from a wave in vacuum by an amount $\phi_f = \frac{2\pi}{\lambda}(n_f - 1)b$. Similarly the phase of the wave $\vec{E}_{i2}$ after the plate differs from the phase of a wave in vacuum by $\phi_s = \frac{2\pi}{\lambda}(n_s - 1)b.$ By superposition, the electric field after the plate is just the sum of the two transmitted waves:

$$\begin{aligned}\vec{E}_t &= \vec{E}_{t1} + \vec{E}_{t2} \\ &= E_0 \cos\theta \hat{e}_1 \cos\left(\omega t - kz - \frac{2\pi}{\lambda}(n_f - 1)b\right) + E_0 \sin\theta \hat{e}_2 \cos\left(\omega t - kz - \frac{2\pi}{\lambda}(n_s - 1)b\right)\end{aligned} \tag{5.20}$$

Question: What is the polarization state?

Answer: Since the wave is of the form (5.9), in general it's elliptically polarized. The wave component amplitudes are $E_{01} = E_0 \cos\theta$ and $E_{02} = E_0 \sin\theta.$ The phases are $\phi_{01} = -\frac{2\pi}{\lambda}(n_f - 1)b$ and $\phi_{02} = -\frac{2\pi}{\lambda}(n_s - 1)b.$

The *retardation* of a waveplate is the difference between the two phases times $\lambda / 2\pi$:

$$\text{Retardation} = \frac{\lambda}{2\pi}(\phi_{01} - \phi_{02}) = (n_s - n_f)b \tag{5.21}$$

It is equal to the extra distance that light would have to travel through vacuum to make a phase difference equal to $|\phi_{01} - \phi_{02}|.$ Retardations are often specified as a number of wavelengths at some given wavelength. For example, a waveplate with a retardation of "1/4 wave at 635 nm" would have a retardation of 635 nm/4 = 158.8 nm.

Quarter- and half-wave plates

A quarter-wave plate is a waveplate with ¼ wave of retardation at a specific wavelength. Quarter-wave plates can be used to produce circularly polarized light from linearly polarized light of that wavelength. You do that by positioning the fast axis at an angle of $\theta = 45°$ to the polarization vector of the incident light. With $\theta = 45°$, the amplitudes $E_0 \cos\theta$ and $E_0 \sin\theta$ of the two polarization components are equal. And with ¼ wave of retardation, the waveplate introduces a phase shift of $\pm\pi / 2$ between the two components. This produces circularly polarized light.

A half-wave plate has a retardation of ½ wave at a specific wavelength. Half-wave plates are used to rotate the polarization of a linearly polarized beam of light at that wavelength, as illustrated in Figure 5.8. If the fast axis of the plate is oriented at angle θ to the polarization vector of the incident light, the amplitudes of the two polarization components leaving the waveplate are $E_0 \cos\theta$ and $E_0 \sin\theta.$ With a retardation of ½ wave, the waveplate introduces a phase shift of $\pm 180°$ between the two components. A phase shift of $\pm 180°$ is equivalent to a phase shift of zero together with a flip in the sign of the amplitude. Thus, the overall effect of the waveplate is equivalent to amplitudes $E_0 \cos\theta$ and $-E_0 \sin\theta$ leaving the waveplate, with no phase shift. Since there is no phase shift, the wave leaving the plate is linearly polarized. It turns out that the output polarization makes an angle of 2θ with respect to the input polarization. One of the most common uses of the half-wave plate is to rotate the polarization of a beam by $90°$, *e.g.* to change the polarization from vertical to horizontal. This is done with a half-wave plate with its fast axis at angle $\theta = 45°$ to the incident polarization.

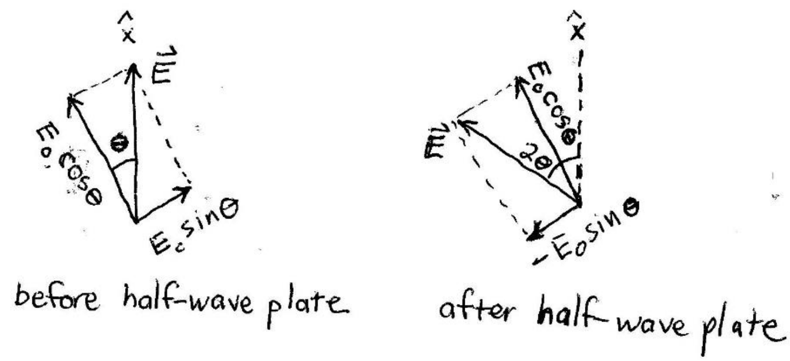

Figure 5.8. Effect of a half-wave plate on linearly polarized light.

Optical activity

Your left and right hands contain a very similar palm, thumb, and fingers, and yet have a structure that is different. This difference is referred to as "handedness." Molecules that exhibit the analogous difference in structure are said to be *chiral*. A chiral molecule always has a left-handed version and a right-handed version. The left-handed version of the molecule is the mirror image of the right-handed version, just as your left hand is the mirror image of your right hand.

Solutions of chiral molecules can rotate the polarization vector of linearly polarized light. This property is referred to as *optical activity*. If the solution causes the polarization vector to rotate clockwise when looking toward the light source, it is said to be *dextrorotatory*. If the solution causes the polarization vector to rotate counterclockwise, it is said to be *levorotatory*. If the left-handed molecule is dextrorotatory, the right-handed molecule will be levorotatory. Or, if the left-handed molecule is levorotatory, the right-handed molecule will be dextrorotatory. Solutions will only be optically active if they contain unequal numbers of left and right-handed molecules.

It might bother that you an asymmetry of molecular structure could have an effect in a solution of those molecules, because the molecules will have a random orientation in the solution. If so, imagine that each molecule has the chiral structure of a spring. When you flip such a spring over, it looks the same. Therefore averaging over different orientations of the molecule does not cause chiral asymmetries to be washed out.

Corn syrup is produced by chemical processing of corn starch. The ordinary type of corn syrup that you buy in a grocery store consists primarily of water (about 20 to 25%), glucose, and larger molecules built primarily out of glucose. This is the type of corn syrup we'll use in this lab. (High fructose corn syrup is further processed to convert about half of the glucose molecules into fructose molecules.)

Since the left and right-handed versions of a molecule are mirror images of each other, there is no reason in theory to expect chemical reactions to favor one version of the molecule over the other. But for reasons that are not well understood, photosynthesis reactions in nature produce glucose of only one handedness. Thus, the glucose molecules in corn syrup are all of one handedness, and it turns out they exhibit strong optical activity.

D. Experimental procedure

Set up the light source and detector

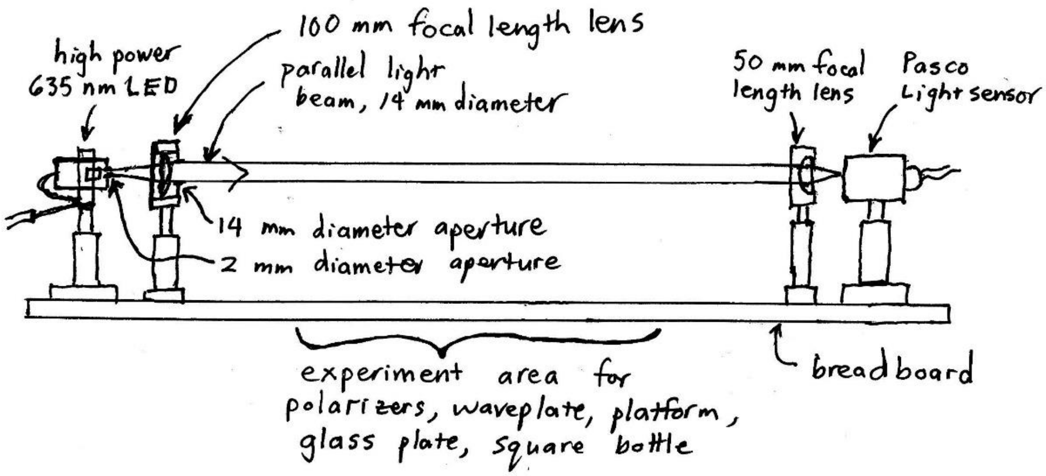

Figure 5.9. Experimental arrangement.

In this experiment we will use a high power light emitting diode (LED) as a light source. This LED puts out 1 Watt of light in a 10 nm wide band of wavelengths centered at about 635 nm. The basic experimental arrangement is illustrated in Figure 5.9. The LED is mounted in a housing that also contains a 2 mm aperture. To begin the lab, secure the LED in its mount to one end of the breadboard. Plug the LED into its supply, and plug the supply into a 120V outlet. The supply can deliver up to 1 Amp of current, but the maximum current for the LED is 0.35 Amp. We have set the supplies to deliver a maximum of 0.35 Amp using the current limit screw adjustment on the side of the supply. With the current limit set in this way, the adjustment knob on the top of the supply varies the output current between 0 Amps and 0.35 Amps. You may operate the LED with any setting of this adjustment knob. However, **do not make any adjustment to the current limit screw on the side of the supply.**

The connector on the cable between the LED and power supply is fragile and easily damaged during a cycle of disconnection and reconnection. For this reason, **do not disconnect the LED cable from the LED power supply.** Leave the LED and power supply connected together at all times, including during storage.

Turn on the LED by rotating the adjustment knob on the top of the supply. The switch should be in the "cw" setting. View the LED output with a screen. You should see a beam of diverging red light. Position the LED so that this beam is 6" above the breadboard. This is important, because that height will work with all the mounts that we have, and with the platform, glass plate, and square glass bottles. The center of the beam should be about 6" above the breadboard throughout the experiment. Also, position the mount so that the beam goes straight down the middle of the breadboard.

Next, place the 100 mm focal length lens with its 14 mm aperture about 100 mm away from the LED. Use one of the pedestal style mounts for the lens so that you can position it wherever you want. Position the lens and the LED so that you make a collimated beam of light that is about 14 mm in diameter all the way down to the other end of the board. You will be making an image of the 2 mm hole, magnified to about 14 mm diameter, somewhere near the end of the breadboard. You will use this beam of light to carry out your experiments. It contains considerably less than 1 Watt of power because much of its output is blocked by the collimation apertures.

Next, position the Pasco light sensor in its mount at the other end of the breadboard. Position the 50 mm focal length lens in its mount in front of the light sensor. Use one of the pedestal-style mounts for this lens, so you can position it wherever you want. Position the lens so that the light beam is centered on the lens, and so that the light beam comes to a focus at the position of the light sensor.

Next, connect the light sensor to the PASCO 850 interface, start the computer, and start up Capstone. Use Hardware set-up to select light sensor for the relevant input channel. Then, drag and drop one "Digits" window and one "Scope" window into the work area, and set both up to display the light sensor output. It is easiest to use the display of the signal on the scope window when making adjustments to the experiment components. However the digits window is better for taking measurements.

Position the light sensor so that you can see a signal in Capstone. Position it so that you maximize the signal. At this stage the sensor sensitivity should be set to x1. Remember that the signal saturates at a value of 100, so if you see the signal go above about 90, turn the LED adjustment knob down. When the light sensor is positioned properly (i.e. the light beam is focused onto the middle of the detector), you should be able to move it one or two mm in any direction without a change in signal level.

Once you have completed this set-up, make sure that all of your mounts are tightened down so they won't move.

Linear polarization measurements

You have three linear polarizers and one half waveplate in mounts. The polarizers are marked with a "P", and the half waveplate with a "1/2". We have marked the transmission axis of the polarizers with two lines on one side of the mount. Light leaving the polarizer will be polarized parallel to the direction indicated by these lines. On the other side of the mount, there is an angular scale marked off in degrees. **The zero of this scale has no special significance**.

Therefore, to measure angles of the polarizer, you must always make two measurements – one of the scale reading for one condition, and a second of the scale reading for another condition. The angle you want to measure will always be the difference of these two readings. You should not depend on the polarizer marks for measuring angles, because they may be off by a few degrees.

Polarization of the light source

Measure the polarization of the light source. To do this, position one of the polarizers in the beam. You should see the power drop. Record the percentage drop in power that you see. Next, rotate the polarizer through 360 degrees. Does the power change? If so, record the maximum and minimum power levels that you see.

Question: Is the light from the LED polarized, unpolarized, or partially polarized? If it is partially polarized, to what degree is it polarized?

Question: The power is reduced after the polarizer because of a combination of two factors. (i) essentially all of the light in the polarization perpendicular to its transmission axis is blocked, and (ii) the polarizer absorbs some fraction of the light that is polarized parallel to its transmission axis. What fraction is this?

Measure transmission through two polarizers as a function of relative angle

Measure the intensity of light transmitted through two polarizers in sequence as a function of the angle θ between their transmission axes. To do this, start by determining the angular reading of the second polarizer when its transmission axis is parallel to the first. (Again, you should set this alignment with measurements of the transmitted intensity, not with the marks on the polarizer, because the marks may be off by a few degrees.) Then, make measurements of the transmitted intensity for something like 10 to 15 different relative angles θ spanning the range from 0 to $360°$. Again, θ will be the difference between the scale reading at each measurement and the scale reading when the polarizer axes are aligned. Fit your data to the function $A\cos^2\theta$ to see if you can confirm Malus' law.

Observe the effect of a third polarizer placed between two crossed polarizers

Place three polarizers in a row, and rotate them so they all transmit vertically polarized light. Record the signal level in this condition. Next, remove the middle polarizer. Rotate the last polarizer so that the transmitted intensity is a minimum. Two polarizers in this condition are said to be "crossed." Now put the middle polarizer back. Rotate that middle polarizer through $360°$ and observe what happens. You should see that some light now makes it through the third polarizer for some angles of the second. Rotate the middle polarizer to an angle that maximizes the transmitted power, and record the signal in this condition. Also take note of the relative angle of the middle polarizer that results in maximum power transmitted.

Questions: How can any light make it through the third polarizer, when the third polarizer and first polarizer are crossed? What is the ratio of the maximum power transmitted with the first and third polarizer crossed to the power transmitted with all three polarizer axes parallel? Explain the value of this ratio.

Rotation of light by a half-wave plate

You are supplied with a half-wave plate for 635 nm wavelength in a mount. The waveplate is labeled with a "1/2". Also, two lines on one side of each waveplate mount show the orientation of its fast axis. On the other side there is an angular scale. The zero on this scale has no special significance. As before, you'll need to take differences of angular readings on this scale to obtain meaningful measurements.

<u>Using a method of your choice, make measurements that show that when a linearly polarized beam is transmitted through a half-waveplate, the output beam is also linearly polarized, at an angle of 2θ to the input beam, where θ is the angle between the waveplate fast axis and the polarization vector of the input beam</u>.

Optical Activity

Measurement: We have prepared bottles with four different mixtures of corn syrup and water: one with 0% corn syrup, one with 10% corn syrup, one with 20% corn syrup, and one with 40% corn syrup. Using these bottles, observe that a solution of corn syrup in water rotates the polarization of linearly polarized light. <u>Measure the rotation angle for the four different mixtures, and determine whether or not the rotation angle is proportional to the concentration of the corn syrup</u>.

Suggested procedure: The beam will be distorted by the poor optical quality of the bottle, so it is is easier to determine angles visually than with the detector. To do this, place the first polarizer, platform, second polarizer, and screen in sequence on the breadboard. (Optional: put a lens in front of the screen to make the spot on the screen smaller and easier to see. Also, you can turn the room lights out.) Set the second polarizer so that the intensity on the screen is minimum. In this condition, the second polarizer is oriented at 90 degrees relative to the first polarizer. Take note of the scale reading of the second polarizer.

Next put one of the bottles on the platform and in the beam. Adjust the position of the bottle so that the beam is as undistorted as possible. Again, rotate the second polarizer so the intensity on the screen is a minimum. The additional angle through which you rotated the polarizer, relative to the angle with no bottle, is the angle by which the liquid in the bottle rotated the polarization. (When determining polarizer angles visually, it is easier to look for the minimum of intensity than the maximum.)

Question: Is the naturally occurring glucose molecule dextrorotatory or levorotatory?

Measurements of optical activity, like the one you have just carried out, are used in practice to measure concentrations of sugar molecules in the food industry and concentrations of other chiral molecules in industrial and scientific applications.

Brewster's angle, and polarization of light by reflection

The reflection of light strongly depends on polarization. We will not discuss the theory of this effect at all, but experimentally it is easy to observe. The most dramatic effect is the complete vanishing of reflection that occurs for one polarization at one angle of incidence. This angle is called *Brewster's angle.*

Place the platform on your breadboard, and tape a piece of paper onto the platform. Place the glass plate on top of the platform and paper so that the light beam is transmitted through the plate, as illustrated in Figure 5.10. Put one polarizer between the LED and the glass plate. Observe the light that is reflected from the glass plate on a screen. To see this beam with the most sensitivity, turn the LED adjustment all the way up, and focus the reflected spot to a smaller size with the 300 mm focal length lens. It would also be best if the room lights were off.

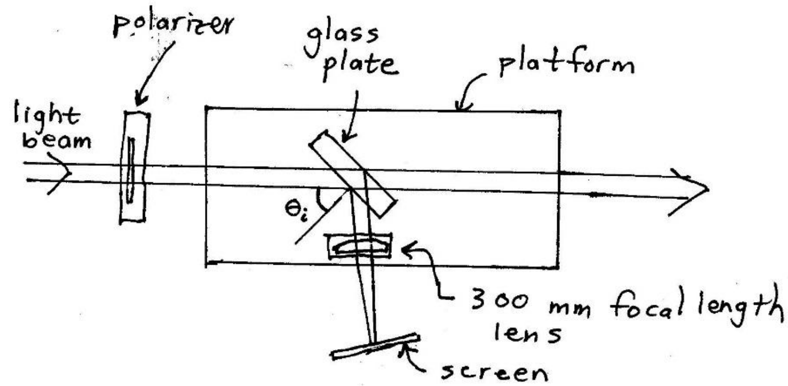

Figure 5.10. Experimental arrangement to measure Brewster's angle. (View from above)

<u>Measure Brewster's angle, and also determine which polarization has zero reflection at that angle</u>. To do this, vary both the angle of the polarizer and the angle of the glass plate, until you find the combination that results in the lowest possible intensity on the screen. You can measure the angle by marking along the base of the plate with a pencil, and by separately marking off the path of one edge of the light beam with a pencil. The angle of incidence θ_i for this situation is Brewster's angle.

Also, <u>observe what happens to the reflected beam when you change the polarizer to the orthogonal polarization</u>.

Question: If the beam of light hitting the glass plate at Brewster's angle is unpolarized, what is the polarization of the reflected light? <u>Check your answer by removing the polarizer from in front of the plate, and using it to measure the polarization of the reflected beam</u>.

Question: If the beam of light hitting the glass plate at Brewster's angle is unpolarized, is the transmitted beam completely polarized, partially polarized, or unpolarized? If it is completely or partially polarized, what is its polarization? (You may also check this with the experiment if you wish.)

Question: Polarized sunglasses are sold because they can block the glare of reflected sunlight, for instance from the water on a lake or ocean. What direction should be used for the transmission axis of the polarizer on these glasses, and why?

Comments: In this experiment, there are actually two overlapping reflected beams, one from the front surface of the glass, and one from the rear surface. The reflections from both surfaces go to zero at Brewster's angle. Surfaces at Brewster's angle are widely used in laser-optical components, because they provide an inexpensive way to get a light beam through an air-to-glass interface with very low loss.