Name ________________________ Date__________ Partners ____

Lab 11 - Polarization

OBJECTIVES

- To study the general phenomena of electromagnetic polarization
- To see that microwaves are polarized
- To observe how light waves are linearly polarized
- To discover alternate ways of polarizing and depolarizing light
- To prove the relationship between orientation and intensity of polarization

OVERVIEW

We have learned previously that electromagnetic waves are time varying electric and magnetic fields that are coupled to each other and that travel through empty space or through insulating materials. Because electromagnetic waves are transverse, the directions of their electric and magnetic fields are perpendicular to the direction in which the wave travels. Fig. 1 shows a periodic electromagnetic wave traveling in the *z*-direction; the electric and magnetic fields are, as always, perpendicular to each other. For periodic electromagnetic waves the frequency and the wavelength are related through

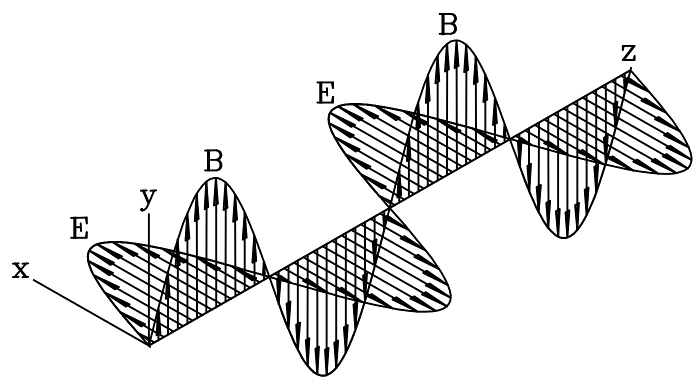

Fig. 1. Periodic electromagnetic wave, **E** = vector of the electric field, **B** = vector of the magnetic field.

$$c = \nu\lambda\,, \tag{1}$$

where λ is the wavelength of the wave, ν is its frequency, and c is the velocity of light. The spectrum of electromagnetic waves spans an immense range of frequencies, from near zero to more than 10^{30} Hz. A section of the electromagnetic spectrum is shown in Fig. 2. In this workshop, we will investigate the polarization of two types of electromagnetic waves that have somewhat different wavelengths and frequencies: microwaves and visible light. We will both produce and analyze polarized waves. When the electric field of the wave is oriented in a particular direction, we say the wave is **polarized**. Unpolarized waves consist of a random mixture of electric field orientations.

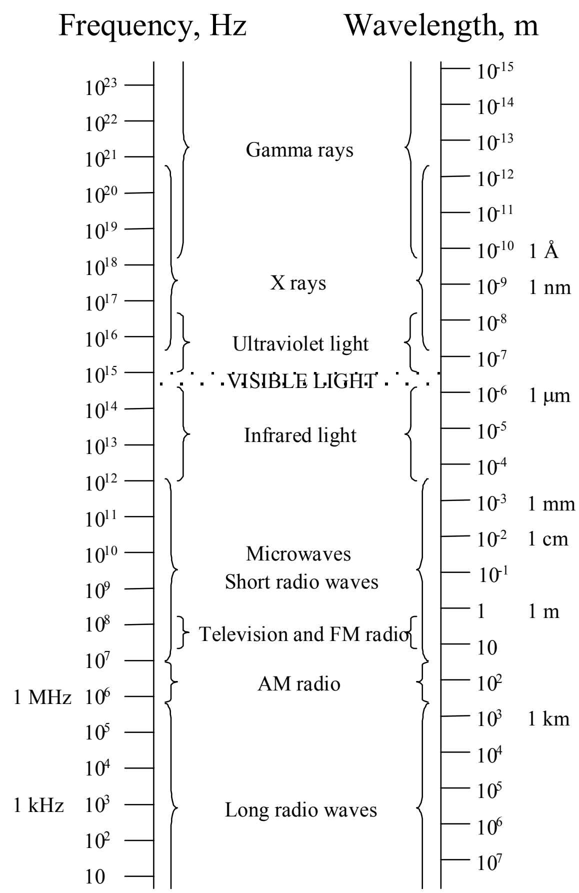

Fig. 2. Section of the electromagnetic spectrum.

Electromagnetic waves are produced whenever electric charges are *accelerated*. This makes it possible to produce electromagnetic waves by letting an alternating current flow through a wire, an **antenna**. The frequency of the waves created in this way equals the frequency of the alternating current. The light emitted by a light bulb is caused by thermal motion that accelerates the electrons in the hot filament sufficiently to produce visible light. The inverse effect also happens: if an electromagnetic wave strikes a wire, it induces an alternating current of the same frequency in the wire. This is how the *receiving* antennas of a radios or television sets work. As one might expect, an antenna is most efficient when its length is of the order of the wavelength of the waves emitted or received. For example, the waves used for TV transmission have wavelengths on the order of one meter.

Investigation 1 will use waves having a frequency of 1.05×10^{10} Hz, corresponding to a wavelength of 2.85 cm. This relegates them to the so-called **microwave** part of the spectrum. In Investigation 2 we will be using visible light, which has wavelengths of 400 –700 nm (nm = 10^{-9}m). Nevertheless, we shall find that both waves exhibit the effects of polarization.

INVESTIGATION 1: MICROWAVE POLARIZATION

For this experiment, you will need the following:

- PASCO Gunn diode microwave transmitter
- PASCO microwave receiver
- Wire grid polarizer

Activity 1-1: Polarization of a Gunn Diode

1. Inside the microwave generator is a solid state device called a **Gunn diode**. When a dc voltage is applied to a Gunn diode, current flows through it in bursts at regular intervals. For your diode, these bursts come at 9.52×10^{-11} seconds apart causing, in addition to the dc current, an ac current at 1.05×10^{10} Hz. As a result, a large ac voltage, oscillating at that frequency, is present across the slot, and so a wave is radiated from the horn. The *electric* field of this wave oscillates in the same orientation as the Gunn diode. The **polarization** of an electromagnetic wave is determined by the direction of the *electric field* vector **E**. The *magnetic field* **B** encircles the current in the Gunn diode and so emanates in the orientation *perpendicular* to **E**. The Gunn diode is placed inside the generator in a way that the electric field will oscillate vertically when the knob on the back is placed at 0º.

2. Examine the microwave receiver. Just inside the horn of the receiver is a detector diode. In addition, there is some circuitry, which amplifies the signals received by the diode and outputs this amplified signal to a d'Arsonval meter and to an external output. The amplification, or alternatively its inverse, the sensitivity, (also labeled METER MULTIPLIER), is controlled via two knobs. The VARIABLE SENSITIVITY knob allows for fine adjustment. As you turn *up* the sensitivity (from 30 to 1), the signal is amplified more and more. To peg the meter means to allow the needle to go beyond the maximum value on the scale. **It is imperative that you NOT peg the meter as doing so can damage it!** If you find the meter pegged, **immediately turn down the sensitivity** and/or **move the receiver away from the microwave generator!**

Prediction 1-1: With what orientation of the wire grid do you expect to find maximum intensity? What does this tell you about the electromagnetic microwaves? With what orientation of the receiver do you expect to find minimum intensity?

CAUTION: DO NOT ALLOW THE RECEIVER'S METER TO PEG AT ANY TIME!

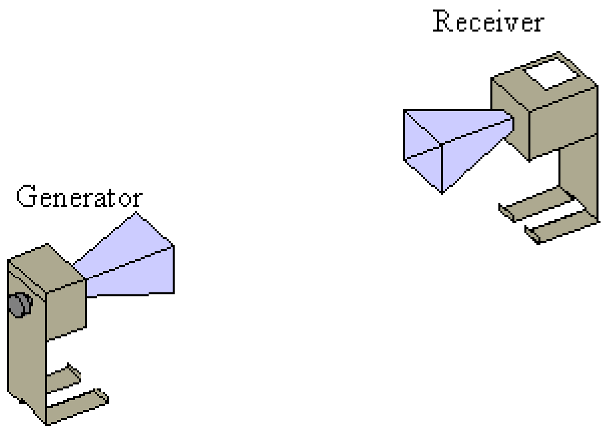

Fig. 3. Use this arrangement to test for polarization.

3. Set up the generator and receiver as shown in Fig. 3.

4. Set the knobs on back of both pieces so the angle indicator is at 0^0. Adjust the sensitivity on the receiver to obtain a signal near 0.5 on the meter. If you cannot achieve this with a sensitivity of 10 or 3, move the receiver closer to the generator. Rotate the *receiver* and verify that it is sensitive to the polarization of the wave. Return the receiver angle to 0º.

Question 1-1: Does it make sense that maximum intensity is obtained when both generator and receiver are oriented the same? Explain why. Why does the received signal go to zero when they are at 90º with respect to one another?

5. Insert the wire grid polarizer (the metal sheet with long slits cut out of it) between the generator and the receiver so that the slits are initially parallel to the direction of the **E** field, which is oriented vertically. Slowly rotate the polarizer so that the slits become perpendicular to the **E** field.

Question 1-2: With what orientation of the polarizer did the receiver indicate the highest intensity? The lowest?

6. Now set the generator's angle to 90º, turn up the sensitivity to 1, and repeat the experiment.

Question 1-3: At what angle for the polarizer wire grid does the meter read a maximum? Can you explain why the receiver gives any signal in this case, because it is turned 90^0 to the generator?

OVERVIEW OF POLARIZED LIGHT

In the remainder of the workshop we will investigate the polarization of visible light. Remember that light is an electromagnetic wave that has coupled electric and magnetic fields that travel through space. The vectors of the electric field **E** and the magnetic field **B** are always perpendicular to each other *and* to the direction in which the light wave travels, as shown in Fig. 4. Because the fields are at a right angle to the direction of propagation, light waves are said to be **transverse waves**.

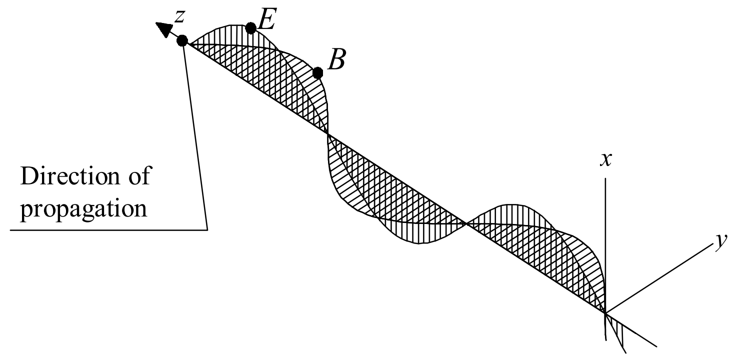

Fig. 4. The electric and magnetic fields are perpendicular to each other and to the direction of propagation.

Even though the vector of the electric (magnetic) field is constrained to be in a plane that is perpendicular to the direction of propagation, infinitely many orientations are still possible in that plane, as shown in Fig. 5. Light from ordinary sources, e.g. the sun, a light bulb, a candle, etc. is a mixture of waves with all these possible directions of polarization and is, therefore, unpolarized.

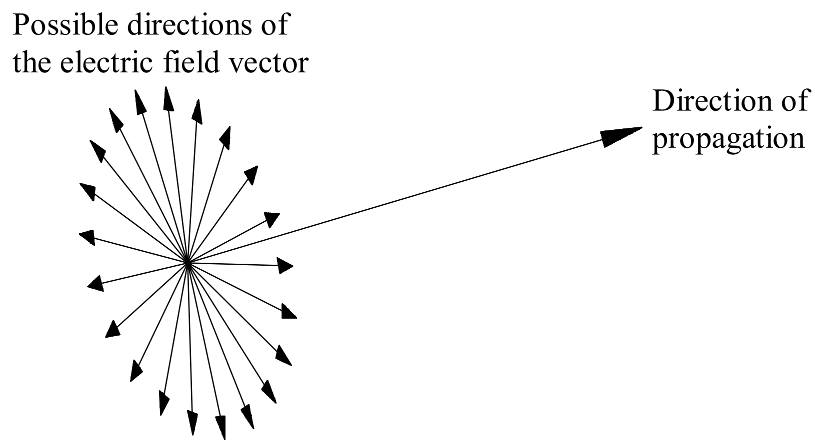

Fig. 5. There are infinitely many possible planes of polarization.

It is, however, possible to produce **linearly polarized light** i.e. light whose electric field vector **E** oscillates always in the same plane, the **plane of polarization**. This plane is spanned by the direction of the electric field and the direction of propagation; it uniquely defines a plane perpendicular to it in which the **magnetic field vector** oscillates.

Polarized light can be obtained in two ways:

1. by using light sources, such as certain lasers, that produce only light with one plane of polarization, or

2. by polarizing unpolarized light by passing it through a **polarizer**, a device that will let only light of one particular plane of polarization pass through.

The wave nature of light was first demonstrated convincingly by Thomas Young in 1801. The polarizability, and thereby the transverse nature, of light was discovered by Etienne Louis Malus in 1809. The electromagnetic nature of light was suggested by Maxwell's theory of electricity and magnetism in 1865.

A wave propagating in the z-direction, whose plane of polarization is the x-z plane, can be described mathematically by the following equation:

$$\mathbf{E}_x = \mathbf{i}E_x \sin\left(\frac{2\pi}{\lambda}(z-ct)\right), \tag{2}$$

where $\mathbf{E}_x$ is the vector of the electric field, E_x its amplitude, and **i** the unit vector in the x-direction. A wave of the same wavelength, polarized in the y-direction, is described by:

$$\mathbf{E}_y = \mathbf{j}E_y \sin\left(\frac{2\pi}{\lambda}(z-ct)+\phi\right). \tag{3}$$

Here, **j** is the unit vector in the y-direction and ϕ is a constant angle that accounts for the possibility that the two waves might not have the same phase. From two such waves one can construct all waves of wavelength λ traveling in the z-direction.

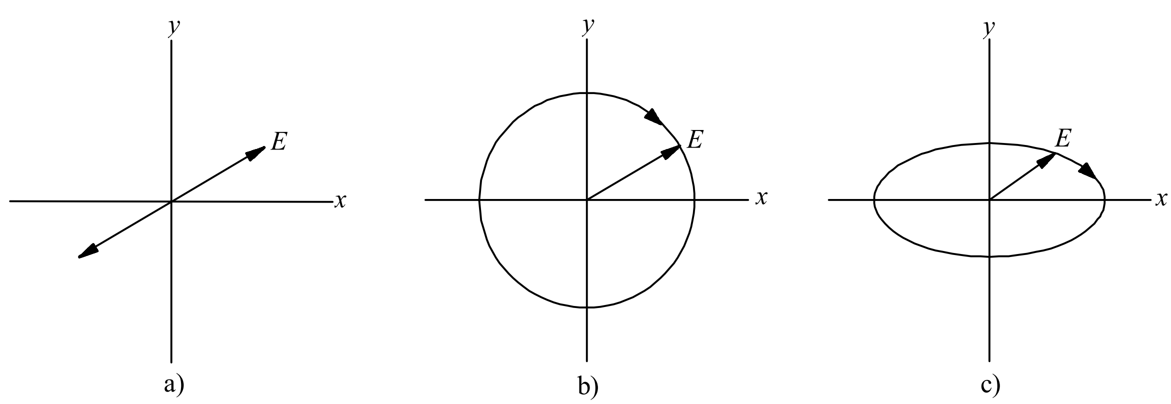

Fig. 6. a) Linear, b) circular, c) elliptical polarization.

If both a x- and a y-component are present and their phase difference is zero or 180°, the wave will be linearly polarized in a plane somewhere between the *x-z* plane and the *y-z* plane, depending on the relative magnitudes of E_x and E_y (see Fig. 6a). Mathematically such a wave is described by:

$$\mathbf{E} = \mathbf{E}_x + \mathbf{E}_y = (\mathbf{i}E_x \pm \mathbf{j}E_y)\sin\left(\frac{2\pi}{\lambda}(z - ct)\right), \qquad (4)$$

where the plus sign refers to a phase difference of 0 and the minus sign to one of 180°. The angle θ between the plane of polarization and the *x-z* plane is given by

$$\tan\theta = \frac{E_y}{E_x}. \qquad (5)$$

If

$$E_x = E_y \text{ and } \phi = \frac{\pi}{2}, \qquad (6)$$

the resulting wave will be circularly polarized, as shown in Fig. 6b, and can be written:

$$\mathbf{E} = \mathbf{E}_x + \mathbf{E}_y = E\left[\mathbf{i}\sin\left(\frac{2\pi}{\lambda}(z - ct)\right) \pm \mathbf{j}\cos\left(\frac{2\pi}{\lambda}(z - ct)\right)\right] \qquad (7)$$

by making use of the fact that $\sin(\alpha + \pi/2) = \pm\cos\alpha$. With the plus sign, this equation describes a wave whose **E** vector rotates clockwise in the *x-y* plane if the wave is coming toward the observer. Such waves are called right circularly polarized. With the minus sign, the equation describes a left circularly polarized wave. If

$$E_x \neq E_y \quad \text{and} \quad \phi = \pm\frac{\pi}{2}, \qquad (8)$$

the **E** vector will still rotate clockwise or counterclockwise but will trace out an ellipse as shown Fig. 6c. If there are many component waves of different E_x, E_y, and ϕ, the resulting wave will be unpolarized.

Linearly polarized light is most easily produced by selective absorption using a **Polaroid Filter**. Such filters, which are available in large sheets, are made by absorbing iodine into stretched sheets of polyvinyl alcohol (a plastic material). In this process the iodine becomes **dichroic**, i.e. its light absorption becomes dependent on the plane of polarization. In a Polaroid filter the component polarized parallel to the direction of stretching is absorbed over 100 times more strongly than the perpendicular component. The light emerging from such a filter is nearly 100% linearly polarized. Figure 7 shows unpolarized light falling on a Polaroid Filter, the polarizer P_1. The direction of polarization is indicated by the parallel lines. *The Polaroid Filters we are using allow the electric field **E** vector of the **transmitted** light to oscillate in the direction of the indicator tab on the*

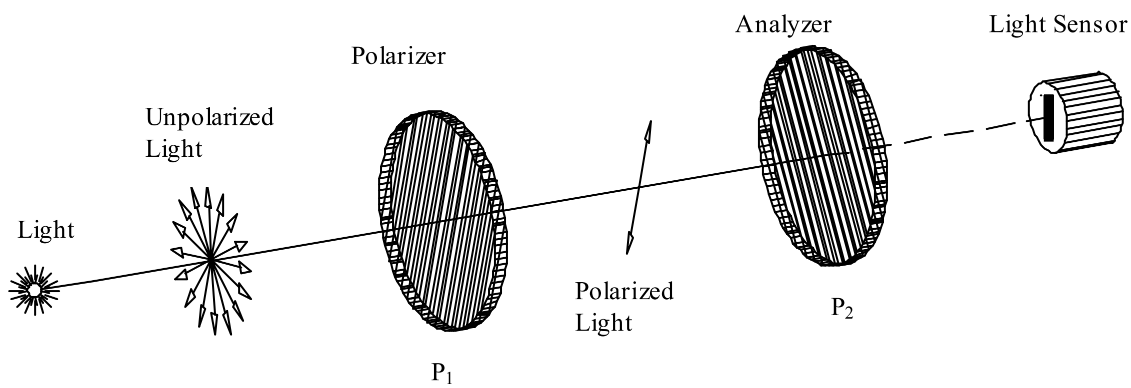

Fig. 7. Polarizer and analyzer.

Polaroid. The sheet will transmit only those vector components that lie in a plane parallel to this direction and will absorb the others. The emerging light is, therefore, linearly polarized. **After unpolarized light passes through a polarizer, the *resulting intensity is half of its initial intensity*, because the light is only transmitted in one direction.** We let I_0 be the initial unpolarized light intensity coming from the light in Fig. 7. Then the intensity I_1 of the light emerging from the polarizer P_1 is $I_1 = I_0 / 2$. If the second Polaroid filter P_2 is rotated about the direction of propagation, one finds two positions, 180° apart, at which the transmitted light intensity is almost zero; these are the positions in which the polarizing directions of P_1 and P_2 are at right angles. In two other positions, 90° apart from the first, almost all the light will pass through. This means that we can use the second filter to *analyze* the polarization of the light coming from the first. For this reason the second filter is usually called the **analyzer**. If the amplitude of the linearly polarized light falling on P_2 is E_1, the amplitude of the light that emerges will be $E_2 = E_1\cos\theta$, where θ is the angle between the directions of polarization of P_1 and P_2. Because the intensity of a light wave is proportional to the square of its electric field amplitude, it follows that the light sensor in Figure 7 should see an intensity I_2 given by:

$$I_2 = I_1 \cos^2\theta + I_B = \tfrac{1}{2} I_0 \cos^2\theta + I_B \tag{9}$$

where I_0 is the intensity of the light entering P_1, I_1 is the intensity of the light between P_1 and P_2, and I_B is a constant background due to ambient light reaching the light sensor without passing through the filters. This is known as Malus' Law, after the French physicist who discovered the polarizing properties of light.

Note: For the next three Investigations, it will be necessary at times to turn off all of the lights in the lab to obtain the best results.

INVESTIGATION 2: POLARIZATION OF A HIGH-INTENSITY LAMP

In this investigation, the unpolarized light from a high-intensity lamp will be linearly polarized. This polarization will be investigated with a second Polaroid analyzer. In addition, a third polarizer will be added to investigate the effect of the orientation of a third polarizer on the intensity.

For this you will need the following:

- Optical bench with lens holders
- Polarizer
- Bausch and Lomb polarized light demonstrator kit
- Small support stand with tripod base
- Desk lamp (high intensity light source)
- PASCO light sensor and cable

Activity 2-1: Linearly Polarized Light and Malus' law

Note: The light sensor that will be used for the rest of the experiments is a PASCO light sensor. It is a photodiode with a sensitivity that ranges from 320 nm to 1100 nm. **Make sure not to allow the output voltage from the sensor to go above 4.75 volts. At this point, the sensor is saturated and you will not get accurate readings.**

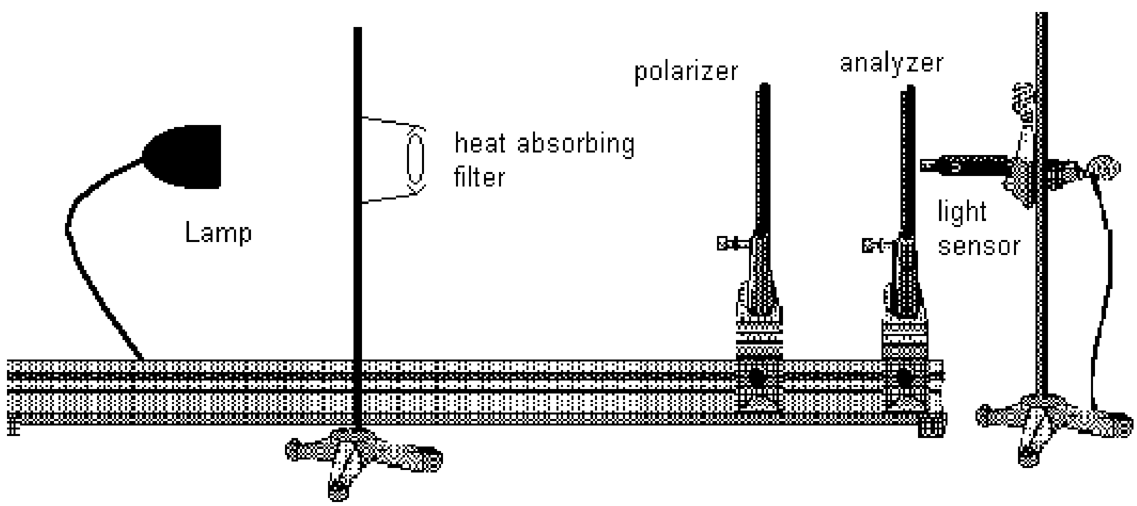

Fig. 8. Setup of the linearly polarized light experiment.

1. Set up the lamp, polarizers, and light sensor as shown in Fig. 8. **DO NOT TURN YOUR LAMP ON YET.** Make sure your lamp is on the opposite end of the table from the computer and is pointing towards the wall, not towards the center of the room. We want to minimize the interference of the light coming from the desk lamp into each other's light sensor.

2. The heat-absorbing filter (item #1 in the box of components) should be mounted on the small support stand in between the light source and the first polarizer.

3. Ensure that the heights of the light, heat absorbing filter, polarizers and light sensor are lined up. Initially rotate the two polarizers 90^0 to each other. Your lamp can now be turned on.

ALWAYS PLACE THE HEAT ABSORBING FILTER BETWEEN THE LIGHT AND THE FIRST POLAROID FILTER TO BLOCK THE INFRARED LIGHT *AND* PREVENT HEAT DAMAGE

Note: The infrared light emitted from the lamp will not be polarized by the filters, but will be seen by the photodetector.

4. Connect the light sensor to channel A in the PASCO interface.

5. Open the experiment file named **Linearly Polarized (L11A2-1)**. There should be a data table when you open the file.

6. In the data table, the first column will be the values for **angle** that you enter. The second column is **Light Intensity**. This column shows the percentage of maximum light intensity that is currently being detected by the sensor. The third column is the **voltage** column. The units for intensity are not volts (they are Lumens), but the output of the light sensor probe is in volts. However, the light intensity and voltage are directly proportional, so any analysis done with volts will be of the correct proportion. **Never let the output from the light sensor exceed 4.75 V**

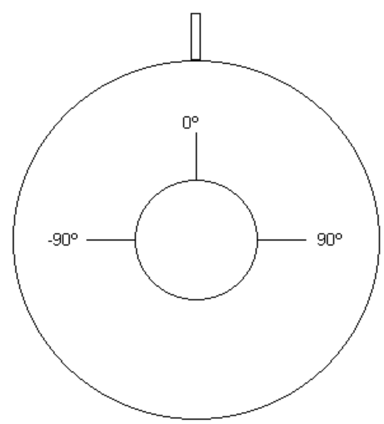

Fig. 9. Convention for measuring angle of polarizer. This diagram is noted while looking toward the light sensor, along the path of the light.

7. Ensure that the light from the lamp is incident on the heat absorbing filter, then travels through

the first polarizer, then through the analyzer, and then onto the light sensor.

8. Start with the two polarizers perpendicular(first one to 0º and second one to -90^0). This is necessary to ensure that the output is not too high.

9. Press **Start** to begin collecting data. The current voltage output from the light sensor will be shown in the digits window and in the third column of the first row. Slowly rotate the second polarizer (analyzer) until it is also at 0^0. **Make sure the sensor reading does not exceed 4.75 volts!** A typical voltage reading when the lamp and sensor are 50-60 cm apart is in the range of 0.5 to 1 V. There is a sensitivity switch on the light sensor that you may need to adjust.

10. Now keep the first polarizer at 0º and set the analyzer to –90º (counterclockwise value; see Fig. 9 for a possible convention). *The Polaroid Filters we are using allow the electric field* ***E*** *vector of the* ***transmitted*** *light to oscillate in the direction of the indicator tab on the Polaroid.*

11. When you feel that the reading has stabilized, press **Keep**. A box will pop up that asks you the angle of the polarizer. Type in "-90" and press Enter.

12. Adjust the analyzer to an angle of -80º. The voltage output will now be shown as before. Press **Keep** and type in the angle.

13. Adjust the angle of the analyzer in 10º steps from -90º to 90º. Repeat step 11 until all of the values are entered, putting in the respective values for the angles. This can go rather quickly with one person changing the angle and another person operating the computer. Once **Keep** has been selected, the next angle can be changed by one group member while another is entering the angle into the computer.

14. When you are finished entering data, click on the red square next to **Keep** to stop data collection.

15. Print out your graph table for your report. Only print one per group. You may need to print it twice to include all the data.

16. At the bottom of the screen, there should two graphs minimized. Bring up the graph titled **I vs. Angle** so you can see the graph of your light intensity plotted versus angle. If you see a fit to your data, you have brought up the wrong graph.

Question 2-1: What does your graph look like? Does it follow the curve you would expect?

17. Minimize this graph, and maximize the second graph titled **Fit Malus L11A2-1**. You will see your data plotted along with a fit. You could have easily entered this fit into Data Studio yourself, but we have done it for you to save time. We have fit intensity I versus angle θ using Eq. (9): $I_2 = \frac{1}{2} I_0 \cos^2 \theta + I_B$.

Question 2-2: Does the fit seem to support Malus' Law? Qualitatively, what does I_B represent? Enter your values below.

Question 2-3: Is it possible that I_B is not constant? Explain. How could you minimize I_B?

18. Print out your graph and attach it at the end of your lab. Only print one per group.

Note: The following experiment will use all of the setup from **Activity 2-1**. Leave everything in place.

Activity 2-2: Three Polarizer Experiment

1. Using the setup from **Activity 2-1**, set the two existing polarizers so that they are crossed (e.g. the polarizer at 90º and the analyzer at 0º).

Make sure to leave the heat absorbing filter in place between the lamp and the polarizers!

Prediction 2-1: What is the orientation of the electric field after it passes through the first polarizer? What will happen to this light when it passes through the second polarizer?

Prediction 2-2: With this arrangement, what output do you expect from the light sensor?

Prediction 2-3: A third polarizer will be added in between the other two. What effect will this have, if any, on the output of the light sensor?

Prediction 2-4: What orientation of the third polarizer (in between the first two) do you expect would produce maximum voltage? Give the angle with respect to the first polarizer. (**Note:** you found this value in your prelab).

2. Place the third polarizer in between the other two.

3. Open the experiment file named **Three Polarizer (L11A2-2)**. There should be two digit displays; one for voltage output and one for intensity. Press **Start** to activate the displays.

4. Adjust only the middle polarizer and find the orientation for which the output shown on the computer is a maximum. Record the angle at which the maximum occurs.

   Angle______________

5. Click on the red square to stop the data collection.

6. Visually confirm this with your own eyes. You will need to move the detector out of the way.

Question 2-4: Do you agree with the angle determined in step 4? If not, explain.

Question 2-5: Explain your findings in terms of the orientation of the electric field after the light travels through each polarizer. Why would the angle found in step 4 produce the maximum intensity?

INVESTIGATION 3: THE HELIUM-NEON LASER AND BREWSTER'S LAW

BREWSTER'S LAW

An alternative way to produce linearly polarized light is based on **Brewster's law**. A wave falling on the interface between two transparent media is, in general, partly transmitted and partly reflected. However, there is a special case in which the directions of the *transmitted* and *reflected* waves are perpendicular to each other, as shown in Figure 10. The component of the wave whose electric vector **E** is *in the plane of the page*, called the p wave, is not reflected at all but completely transmitted when the incident angle is α (called Brewster's angle) from the normal. The p wave is represented by the short lines in the figure. Meanwhile, the reflected light contains the remainder of the wave, the component whose electric vector oscillates *perpendicular to the plane of the page*. Therefore, the light that is reflected is totally polarized. This second wave is usually called the σ wave and is symbolized by dots (•) in the figure.

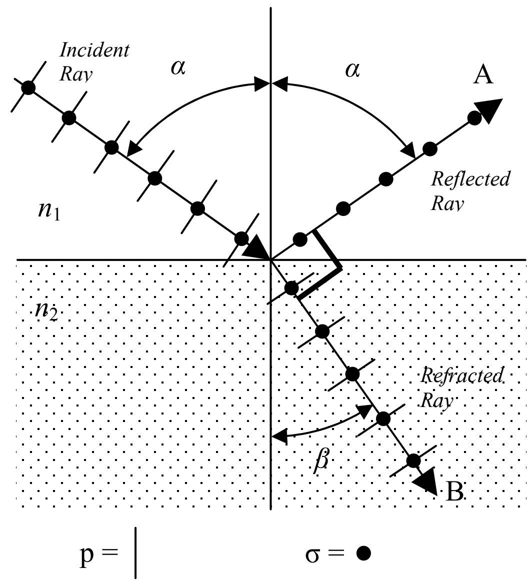

Fig. 10. Reflection at the Brewster angle. The p wave is *in* the page, while the σ wave is *perpendicular to* the plane of the page. Note that $\alpha + 90° + \beta = 180°$.

This surprising effect can be understood qualitatively in the following ways. First, if the reflected wave at Brewster's angle were to contain *some* of the p wave, that part of the electric field would oscillate along the direction of the wave. In other words, the reflected wave would contain a longitudinal component. However, we know light to be purely a transverse wave, so the reflected wave at Brewster's angle cannot have any part of the p wave in it.

Second, light propagates through a medium such as glass by setting its electrons oscillating perpendicular to the direction of the light (in the plane of the electromagnetic fields). The electrons in the medium then re-emit the wave perpendicular to their motion and in the direction of the original wave. An observer viewing the surface from point A in Fig. 10 looks edge on at those oscillators that transmit the p wave. In other words, the electrons driven by the electric field of the p wave oscillate toward and away from A. However, the oscillators cannot emit any energy (light) in that direction, so the observer at A cannot "see" this light from the p wave. It is traveling in another direction. In contrast, the oscillators that transmit the σ wave are perpendicular to the plane of the paper. From the perspective of the observer at A, the electrons at the surface oscillate to the left and right. The light they (re-)emit is most intense when viewed from anywhere in the plane of the page, for example from points A and B. The reader viewing the figure from out of the page cannot see the σ wave.

The angle of incidence satisfying the condition of Brewster's law, called **Brewster's angle** (angle α), is easily obtained from Fig. 10. Noting that

$$\beta = \frac{\pi}{2} - \alpha \tag{10}$$

and using Snell's law ($n_1 \sin\alpha = n_2 \sin\beta$, where n_1 is the index of refraction of the medium containing the incident ray, and n_2 is the index of refraction of the medium containing the refracted ray), we can show:

$$\frac{n_1}{n_2} = \frac{\sin\alpha}{\sin\beta} = \frac{\sin\alpha}{\sin\left(\frac{\pi}{2} - \alpha\right)} = \frac{\sin\alpha}{\cos\alpha} = \tan\alpha\ . \tag{11}$$

In the case that you will be looking at in class, the index of refraction of the first medium, n_1, is equal to the index of refraction of air. For these purposes, this will be taken to equal 1. Putting this into Eq. (11), it can be shown that:

$$n = \tan\alpha \tag{12}$$

where n is the index of refraction of the glass plate.

Brewster's law is just a special case of the **Fresnel equations** that give the amplitudes of the transmitted and reflected waves for all angles.

The polarization upon reflection is rarely used to produce polarized light since only a few percent of the incident light is reflected by transparent surfaces and become polarized (metal surfaces do not polarize light on reflection). But the fact that light reflected by glass, water, or plastic surfaces is largely polarized enables one to cut down *glare* with Polaroid glasses or Polaroid photographic filters.

(Note: The blue light of the sky is produced by the scattering of sunlight in the air. This light is partly polarized and Polaroid filters can be used to reduce the haze obscuring distant views.)

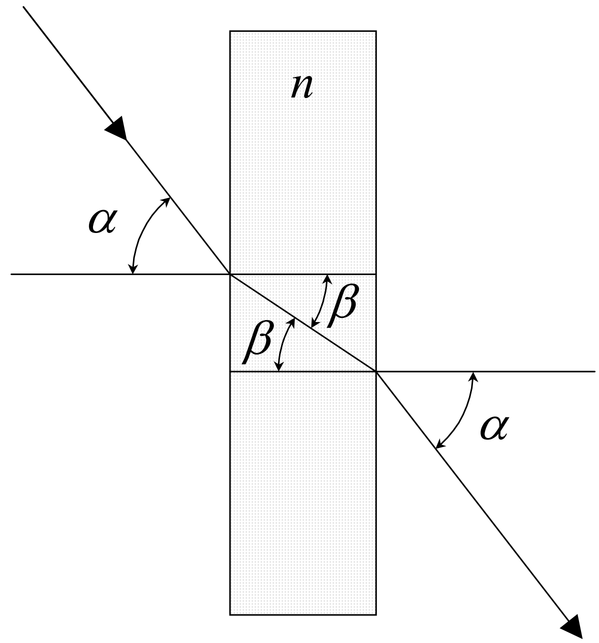

Fig. 11. Brewster window.

If one shines light under the Brewster angle onto a plane parallel glass plate, as shown in Fig. 11, the Brewster condition is satisfied at both the entrance and the exit face. This means that the p wave is transmitted without reflection by both surfaces. Such an arrangement is called a **Brewster window**.

Brewster windows are used in gas lasers as shown in Fig. 12. The p wave will be completely transmitted by both windows, enabling the external reflectors to establish the standing wave necessary for laser operation.

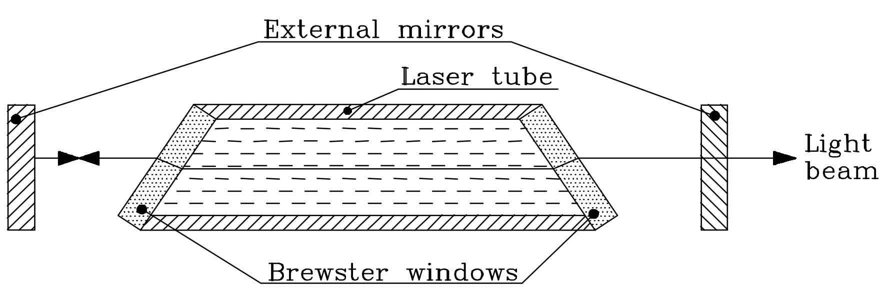

Fig. 12. Brewster windows in a gas laser.

The component whose electric vector is perpendicular to the plane of the figure (the σ wave) is partially reflected by the Brewster windows so that a standing wave of sufficient intensity for laser operation cannot be established with this polarization. Lasers of this kind produce light that is plane-polarized in the plane of the paper. Lasers whose reflectors are inside the gas-filled tube can oscillate simultaneously in both polarization modes and will produce unpolarized light.

In this investigation, a Helium-Neon (He-Ne) laser will be used. First, its polarization will be tested with an analyzer. Then, it will be used to test Brewster's Law.

For this investigation, you will need the following:

- Bausch and Lomb polarized light demonstrator kit
- Optical bench with lens holders
- Small support stand with tripod base
- He-Ne laser
- Collimator
- Spectrometer stand
- PASCO light sensor
- Desk lamp
- Slide containing paper to block out light

WARNING: LASER LIGHT CAN DAMAGE THE EYES. NEVER LOOK DIRECTLY INTO THE BEAM OR AT LASER LIGHT REFLECTED FROM METAL, GLASS OR POLISHED SURFACES.

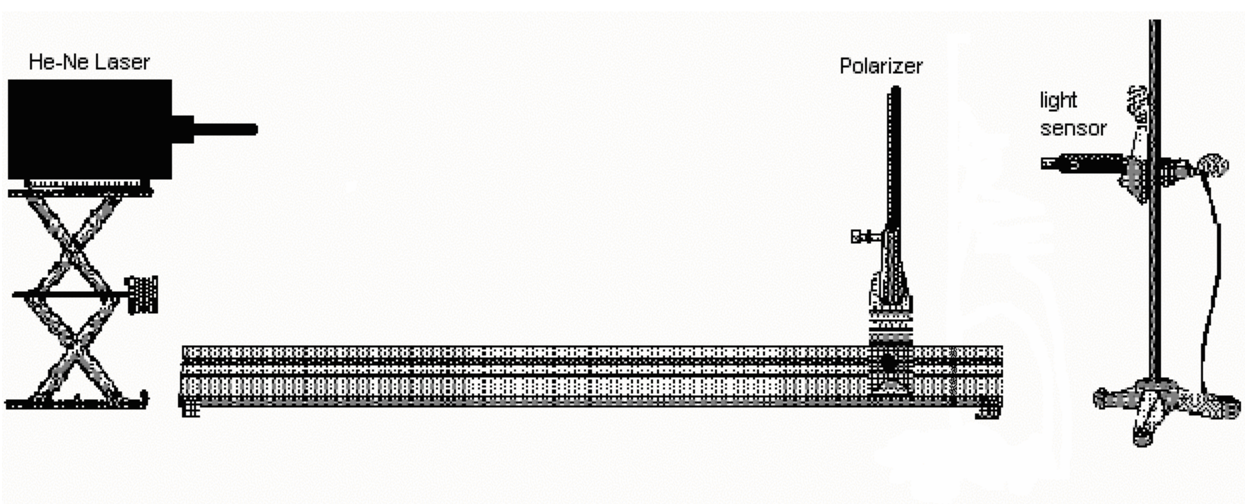

Fig 13. Setup of **Activity 3-1**.

Activity 3-1: Polarization of the He-Ne Laser

This activity will determine whether or not the light from the laser is linearly polarized by shining the laser beam through a (single) polarizer into the light sensor and measuring the output while rotating the polarizer.

Note: The laser beam is quite intense and can easily overload the light sensor. Therefore, make sure the beam expander (collimator) is on the laser. **The output from the light sensor should read no more than 4.75V. Perhaps cover the light sensor until you are ready to measure.**

1. Place one polarizer on the optical bench.

2. Adjust the height of the He-Ne laser so it is incident upon the polarizer and therefore the light sensor.

3. Open **Three Polarizer L11A3-1**. This will be used as a meter to observe the voltage output.

4. When you are ready, press **Start** to begin collecting data.

5. Rotate the polarizer until a maximum voltage has been obtained. Record your angle.

Angle ____________

Question 3-1: Based on your observations, would you say that the laser produces linearly polarized light? Why or why not?

Question 3-2: In what direction is light from the laser polarized?

Note: The tubes inside the laser box are not necessarily aligned so that the laser light is aligned perpendicular or parallel to the base of the laser box. It most likely will be at some other angle. Do not assume the laser light is polarized in some special orientation. You have just measured the direction of polarization for *your* laser.

6. Click on the red square to stop data collection.

Activity 3-2: Determination of Brewster's Angle

Prediction 3-1: You will be using crown glass as your Brewster window in the following experiment. What angle do you expect to find, knowing the index of refraction of crown glass (see Appendix A)? If you found this in your prelab, record the value below.

1. Mount the 2.5" glass plate in the slot atop the small turntable. Use the nylon screws to hold the plate in place perpendicular to the stand. This will serve as your Brewster window. Place the turntable on the table next to the middle of the optical bench. Do not move the optical bench! It is very fragile. See Fig. 14.

2. Unscrew the collimator from the laser so that the laser emits a single pencil of light. Place the laser on its side so that the laser light produced is mostly polarized in the horizontal plane. Rotate the position of the laser on the lab jack so that its light is incident upon the glass plate. The distance between the laser and glass plate should be about 50 cm, but this does not require a measurement.

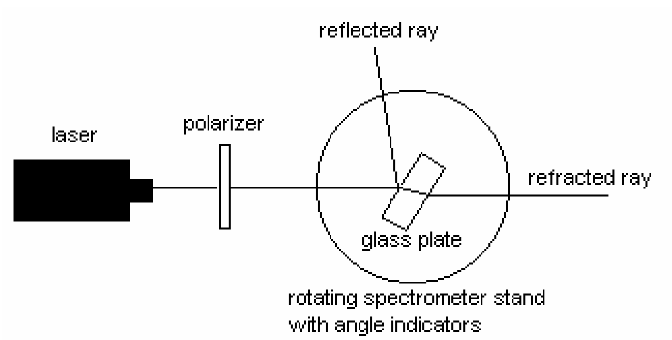

Fig. 14. Diagram looking from above the apparatus. The light from the laser travels through the polarizer and to the glass plate, where some of it is reflected and some is refracted.

3. Place a polarizer and holder on the table in between the laser and the glass plate, so the light travels through the polarizer.

Question 3-3: According to the discussion of Brewster's angle, only the σ wave is reflected at the Brewster angle (see Fig. 10). If the σ wave is not present in the incident light, then the Brewster's angle can be found quite easily; it will be the point at which no light is reflected. We want to utilize the polarizer to only allow the p wave to be transmitted through the polarizer. Then all the light will be transmitted through the glass and none will be reflected when the plate is at the Brewster's angle. At what angle should we set the **polarizer** to allow only the p wave to be transmitted?

Polarizer angle for only p wave transmission: _________________

Note: Make sure that the polarizer does not completely block the laser light. To check this, look at the glass plate to ensure that there is light incident upon it. Also try to find the refracted beam. No matter what the angle of the glass plate is with respect to the beam, there will always be a refracted (transmitted) beam – the p wave is always refracted.

4. Set the polarizer at the angle you just determined in Question 3-3.
5. Let the reflected light fall upon a notebook size piece of white paper as a screen to show the reflected ray, rotate the turntable until you find the position at which the intensity of the light reflected by the plate becomes a minimum.

Note: Be careful to position the laser beam so that it does not leave the glass plate as you rotate the spectrometer stand. **Do not let the laser beam shine into the computer screen or the light sensor.**

6. Read the angle on the spectrometer for the position for which the light is a minimum.

   θ ________

7. Rotate the glass plate until the laser beam is reflected back into the laser. Read the angle on the spectrometer again and consider this your *zero angle*.

   θ_0 ________

8. Find the value for $|\theta - \theta_0| = \alpha$. This is your **Brewster's Angle**.

   α ________

Question 3-4: Does your experimental value of the Brewster's angle agree with your Prediction 3-1? If not, explain.

Note: Make sure to replace the diverger on the He-Ne laser by screwing it back on.

If you have time, try to do Investigation 4.

INVESTIGATION 4: OTHER METHODS FOR POLARIZING AND DEPOLARIZING

DEPOLARIZATION

To change polarized light into unpolarized light one must introduce random phase differences between the two components of the electric vector. This can be accomplished by interposing a material that is both inhomogeneous and anisotropic across the wave front.

BIREFRINGENCE

Most of the transparent materials that one encounters daily, such as glass, plastics, and even crystalline materials such as table salt, are optically isotropic, i.e. their index of refraction is the same in all directions. Some materials, however, have an optically favored direction. In these materials the index of refraction depends on the relative orientation of the plane of polarization to that preferred direction. Such materials are called **birefringent** or **doubly refracting**. The best known example of such materials is calcite ($CaCO_3$). Optically isotropic materials, such as glass, can be given a preferred direction, and thus made to be birefringent, by stressing or bending them.

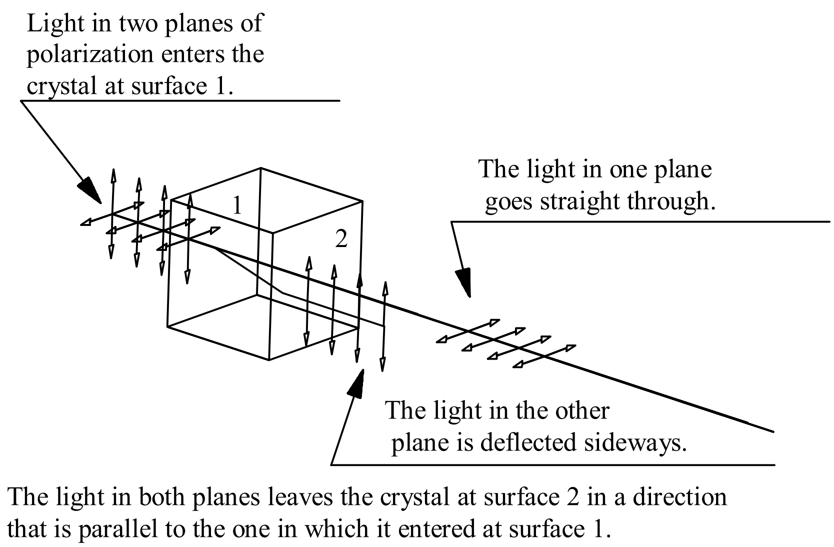

Fig. 15. Light passing through a birefringent crystal.

Consider a light wave traversing a birefringent crystal, as shown in Fig. 15. The propagation direction is perpendicular to the cystal's surface. An initially unpolarized light beam will split into two separate linearly polarized beams. One of these is called the **ordinary ray** or **o-ray** and the other the **extraordinary ray** or **e-ray**. The behavior of the o-ray is essentially that of a ray in an isotropic medium: it is refracted in accordance with Snell's law, and its refractive index n_o is independent of the direction of travel. The e-ray, on the other hand, behaves in a most peculiar way. Its index of refraction n_e depends on the orientation of the crystal. Moreover, its direction of travel, after entering the crystal is not consistent with Snell's law. As Fig. 15 shows it will be refracted even if its angle of incidence is 90°. On leaving the crystal it becomes again parallel to the direction of incidence but displaced with respect to the incident beam. Since the two emerging rays are linearly polarized along mutually perpendicular directions doubly refracting crystals make very effective polarizers: If one cuts a birefringent crystal so that the e-ray, but not the o-ray, is totally reflected at the exit face one can produce light that is 99.999% linearly polarized.

Another application of birefringence is the **quarter-wave plate**, a device that can be used to convert linearly into circularly polarized light and vice versa. Consider again Fig. 15: Not only do the e- and the o-rays experience a different coefficient of refraction, but they also travel different distances in the crystal. As a result they will be out of phase with respect to one another. Through a suitable choice of the thickness of the crystal one can arrange it that the phase difference between the two rays becomes a quarter of a wavelength, in which case a linearly polarized incident light beam will be circularly polarized on leaving the crystal.

The wavelength dependence of the index of refraction, although small, lends itself to some pretty demonstration experiments. If one places two Polaroid filters in front of a light source so that their directions of polarization are perpendicular to each other, they will appear dark. If one then places an object made of a birefringent material between the crossed

Polaroids, a multicolored image of the object will become visible in the previously dark field. The o-ray and the e-ray have traveled different optical path lengths and their phases, upon leaving the object, will differ, the difference being a function of the wavelength of the light. Since the two rays are polarized in different directions they cannot interfere with each other. The second Polaroid (the analyzer) passes that component of each ray whose plane of polarization is parallel to the direction of polarization of the filter. These components have the same plane of polarization and can interfere. Whether their interference is constructive or destructive will depend on their phase difference and hence on their color.

In this investigation, you will use different objects and materials to both polarize and depolarize light. You will need the following materials:

- Bausch and Lomb polarized light demonstrator kit
- Optical bench with lens holders
- 2 small support stands with tripod base
- Laser
- Water tank
- Collimator
- Desk lamp
- PASCO light sensor

Activity 4-1: Depolarization

As you will recall from the readings above, random phase differences may be introduced between the two components of the electric field vector to depolarize the light.

1. Set up two polarizers with the desk lamp and heat-absorbing filter as done in Investigation 2. Remove the light sensor and unplug it from the PASCO interface. You will be looking with your eye. Set the first polarizer to 0^0.

Prediction 4-1: With this setup, what do you expect to be the relationship between intensity and angle of the second Polaroid (analyzer) with respect to the first polarizer? (Hint: we did this in Investigation 2).

2. Place the piece of wax paper from the polarizing kit in between the two polarizers by holding it in the second small support stand.

Prediction 4-2: With the wax paper added, do you expect the relationship between intensity and angle to change? Why or why not? What do you expect the new relationship will be, if you think it will change?

3. Look with your eye towards the light source where the light sensor would be as you rotate the polarizer through 180º.

Question 4-1: Describe the transmitted light intensity as you rotate the polarizer. What does this show you about the polarization of the light through the wax paper?

Activity 4-2: Birefringence by the Calcite Crystal

1. Set the calcite crystal from the polarization kit on the dot to the right.
2. Hold a polarizer over the calcite and look through it at the text. ●

Question 4-2: What do you observe and with and without the polarizer?

3. Slowly rotate the polarizer until only one dot is seen. Note the orientation of the polarizer.

   θ_1 ___________ (choose a relative zero angle)

4. Rotate the polarizer again until the other dot is shown. Note the orientation of the polarizer.

   θ_2 __________ (use same zero angle as before)

Question 4-3: What does this tell you about the relative polarization of the images created by the calcite crystal?

Activity 4-3: Interference Caused by Birefringence

1. Insert the mica sample between two crossed polarizers (set at 90º and 0º, for example) and look through the setup at the lamp.

2. Tilt the mica sample slowly backwards as shown in Fig. 16.

Question 4-4: What do you see?

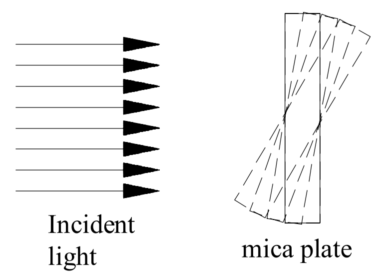

Fig. 16

Question 4-5: Do your observations depend on the angle at which you hold the mica?

Activity 4-4: Birefringence Due to Stress

Replace the mica with the U-shaped piece of plastic between the crossed polarizers.

1. Look through the polarizer at the plastic.

Question 4-6: What do you observe? Do you see light?

Question 4-7: Based on your previous observations, is the light polarized by the plastic? Why or why not?

2. Lightly squeeze the two legs of the U toward each other while looking at the plastic through the polarizer.

Question 4-8: What do you observe?

Question 4-9: What has changed about the light through the plastic?

Comment: The strain partially orients the molecules and makes the plastic birefringent. From such patterns engineers can locate regions of high strain in a plastic model of a structure and then decide whether the structure must be redesigned or strengthened in certain places.

Question 4-10: In which corner of your plastic is there the greatest stress?

Activity 4-5: Polarization of Scattered Light

Sunlight is scattered while passing through the atmosphere. Light with a short wavelength is scattered more than light with a long wavelength. This is why the sky appears blue. Light scattered by 90° is strongly polarized. You can verify this on a clear day if you look through a Polaroid filter in the appropriate direction of the sky. A similar observation can be made in the laboratory by passing laser light through a tank of water that has been clouded by suspending some scattering material in it. The laser beam should already be passing through the tank.

1. From the side of the tank, at a right angle with respect to the direction of the light, examine the scattered light using a polarizer.

Question 4-11: What is the degree of polarization as a function of polarizer angle? Answer qualitatively.