Lab 8: Polarization of Light

1 Introduction

Refer to Appendix D for photos of the apparatus

Polarization is a fundamental property of light and a very important concept of physical optics. Not all sources of light are polarized; for instance, light from an ordinary light bulb is not polarized. In addition to unpolarized light, there is partially polarized light and totally polarized light. Light from a rainbow, reflected sunlight, and coherent laser light are examples of polarized light. There are three different types of polarization states: linear, circular and elliptical. Each of these commonly encountered states is characterized by a differing motion of the electric field vector with respect to the direction of propagation of the light wave. It is useful to be able to differentiate between the different types of polarization. Some common devices for measuring polarization are linear polarizers and retarders. Polaroid sunglasses are examples of polarizers. They block certain radiations such as glare from reflected sunlight. Polarizers are useful in obtaining and analyzing linear polarization. Retarders (also called wave plates) can alter the type of polarization and/or rotate its direction. They are used in controlling and analyzing polarization states.

This experiment consists of a series of basic exercises, which will introduce important techniques for analyzing the polarization of light. We will study linear and circular polarization, using linear polarizers and two types of retarders: quarter-wave and half-wave. The first two parts of the experiment deal with testing the polarization of a laser and analyzing it using linear polarizers. In the third part of the experiment, you will use quarter wave plates to produce circularly polarized light and investigate its properties. Finally, you will use a half-wave plate to rotate the direction of linear polarization.

EXERCISES 1-5 PERTAIN TO THE BACKGROUND CONCEPTS AND EXERCISES 6-11 PERTAIN TO THE EXPERIMENTAL SECTIONS.

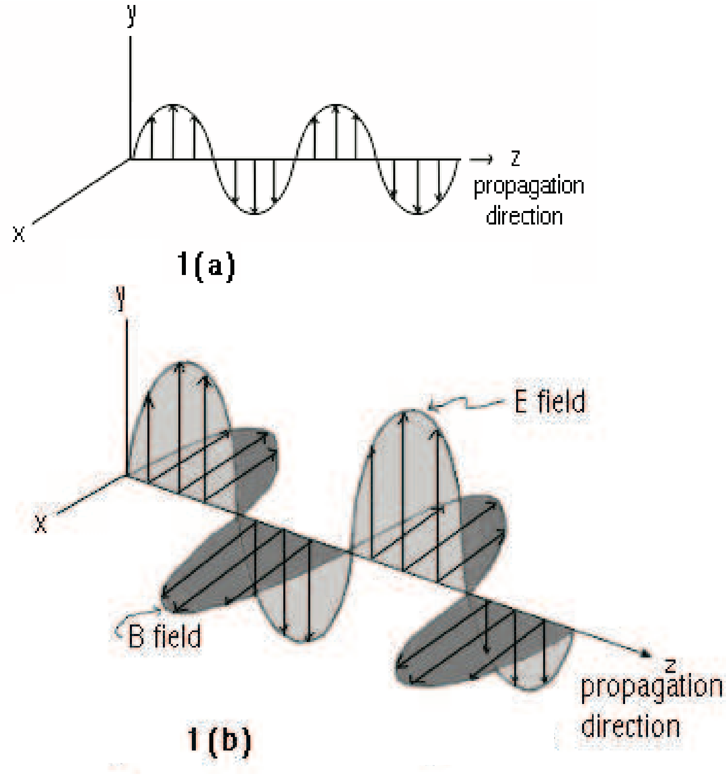

Figure 1: (a)Oscillation of E vector, (b)An electromagnetic field.

2 Background

Light is a transverse electromagnetic wave. Its propagation can therefore be explained by recalling the properties of transverse waves. Picture a transverse wave as traced by a point that oscillates sinusoidally in a plane, such that the direction of oscillation is perpendicular to the direction of propagation of the wave. The oscillating point can be considered to describe the vibration of the electric field vector **E** of the light wave, as shown in Figure 1(a). The magnetic field vector **B** vibrates in a direction perpendicular to that of the electric field vector and to the direction of propagation of the wave, as shown in Figure 1(b). The magnetic field is very weak and therefore it is ignored in our study of polarization. In figures 1a and 1b, only one electric field vector is shown. However, light emitted from an actual source consists of many such electric field vectors. The polarization of light is defined in terms of the direction of oscillation of the electric field vectors. An ordinary source of light (such as the Sun) emits light waves in all directions. Consequently, the electric field vectors vibrate randomly in all directions. Such sources of light are **unpolarized** (Figure 2(a)). **Partially polarized** light occurs if the E vectors have a preferred direction of oscillation (Figure 2(b)). Light is **totally linearly polarized**

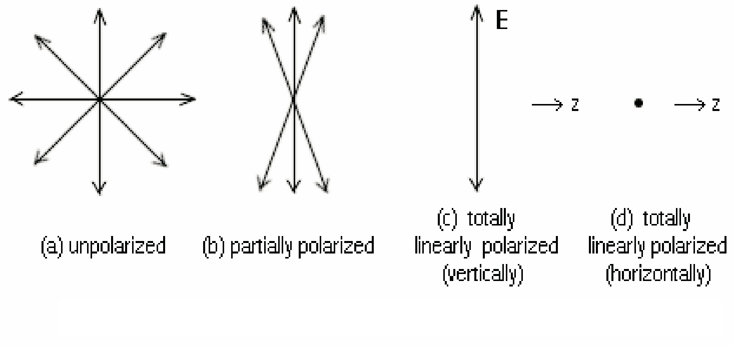

Figure 2: Polarization of light, z is the direction of propagation.

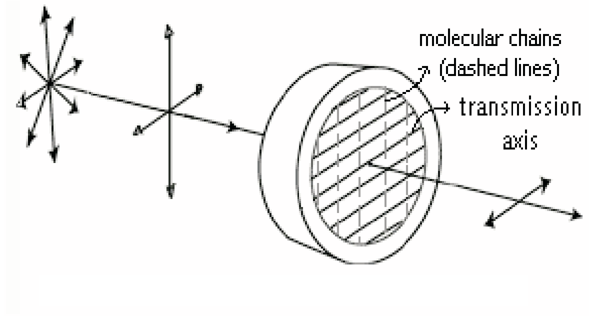

Figure 3: Transmission through a linear polarizer.

(or **plane polarized**) if all the electric field vectors oscillate in the same plane, parallel to a fixed direction referred to as the polarization direction. The special case of vertically polarized light is represented by a vertical arrow (Figure 2(c)), while the special case of horizontally polarized light is represented by a dot indicating that the E vector oscillates into and out of the page (Figure 2(d)). For linearly polarized light, the plane of polarization is defined as a plane parallel both to the direction of oscillation of the electric field vector and the direction of propagation of the wave. The behavior of electromagnetic waves can be studied by considering two **orthogonal** components of the electric field vector. The phase relationship between these two components can explain the different states of polarization. For example, if the phase relationship is random, light is not polarized. If the phase relationship is random, but more of one component is present, the light is partially polarized. If the phase relationship is constant, the light is completely polarized. More specifically, if the phase difference is 0 or 180 degrees, the light is **linearly** polarized. If the phase difference is 90 or 270 degrees and both components have the same amplitude, the light is **circularly** polarized. If a constant phase difference other than 0, 90, 180 or 270 degrees exists and/or the amplitudes of the components are not equal, then the light is **elliptically** polarized. In case of circular or elliptical polarization, the plane of polarization rotates, in contrast to linear polarization where the plane of polarization is fixed. There are two directions of circularly (or elliptically) polarized light. Right-hand circularly polarized light is defined such that the electric field is rotating clockwise as seen by an observer towards whom the wave is moving. Left-hand circularly polarized light is defined such that the electric field is rotating counterclockwise as seen by an observer towards whom the wave is moving0.

Elliptical polarization is not studied in this experiment. A mathematical treatment of linear and circular polarization and their interaction with polarizers and retarders will be presented next.

Linear polarizers: Certain materials have the property of transmitting an incident unpolarized light in only one direction. Such materials are called dichroic. Polarizing sheets (which are **dichroic**) are manufactured by stretching long-chained polymer molecules after which they are saturated with dichroic materials such as iodine. Then they are saturating with dichroic materials such as iodine. The direction perpendicular to the oriented molecular chains is called the **transmission axis** of the polarizer. A polarizing sheet has a characteristic **polarizing direction** along its transmission axis. **The sheet transmits only the component of the electric field vector parallel to its transmission axis.** The component perpendicular to the transmission axis is completely absorbed (this is called selective absorption). Therefore, light emerging from the polarizer is linearly polarized in the direction parallel to the transmission axis. Figure 3 illustrates this idea. The linear polarizer is oriented such that its transmission axis is horizontal. Light incident on the polarizer is unpolarized. However, the E vectors of the unpolarized light can be resolved into two orthogonal components, one parallel to the transmission axis of the polarizer, and the other perpendicular to it. Light emerging from this linear polarizer is lineraly polarized in the horizontal direction. It is also worth noting that polarizers reduce the intensity of the incident light beam to some extent.

Retarders (waveplates): A retarder (or waveplate) resolves a light wave into two orthogonal linear polarization components by producing a phase shift between them. Depending on the induced phase difference, the transmitted light may have a different type of polarization than the incident beam. Note that retarders do not polarize unpolarized light and ideally

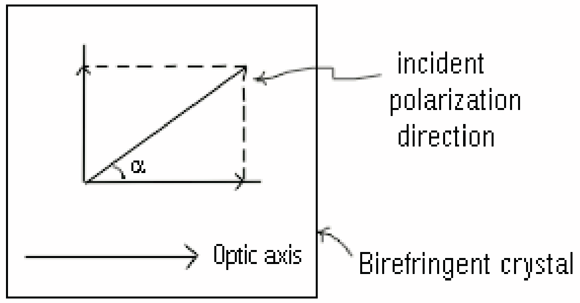

Figure 4: Splitting of linearly polarized light into two components as it enters a birefringent crystal.

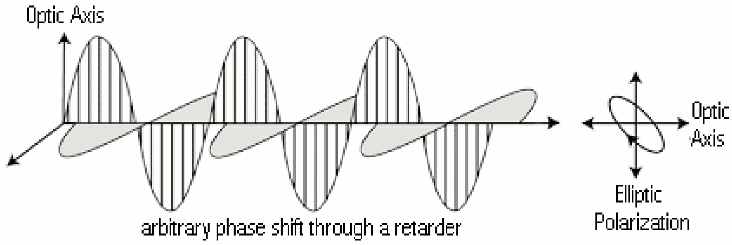

Figure 5: Conversion of linear polarization to elliptical polarization.

they don't reduce the intensity of the incident light beam.

To understand how retarders function, it is instructive to consider the nature of the materials used in their construction. A material such as glass has an index of refraction n, which is the same in all directions of propagation through the material. Therefore when light enters glass, its speed will be the same in all directions (v=c/n). Such materials having one index of refraction are called **isotropic**. Certain materials such as quartz exhibit double refraction or **birefringence** and are characterized by two indices of refraction (along directions of crystalline symmetry): an ordinary index and an extraordinary index. These materials are called **anisotropic** and the speed of light through them is different in different directions. Normally, as light enters such a material, it splits into two components: an ordinary ray along an ordinary axis (O) and an extraordinary ray along an extraordinary axis (E). These two components travel at different speeds along different directions, which results in a phase difference between them. However, if light is incident on the crystal such that the plane of incidence is parallel to a characteristic direction called the **optic axis**, both rays travel in the same direction and with the same speed (This is why these crystals are called **uniaxial**). Figure 4 shows linearly polarized light incident on a birefringent crystal. The light splits into two components parallel and perpendicular to the optic axis. A phase shift between the two components is induced. Birefringent materials are the basis of the construction of retarders because they can introduce a phase difference between the two components of the electric field incident on the retarder. Figure 5 shows an arbitrary phase shift between the two components of the E vector of Figure 4 as they pass through a retarder; linear polarization is thus converted to elliptical polarization due to the arbitrary phase shift. The phase difference depends on the incident wavelength, the refractive indices (along the two different directions) and the thickness of the crystal. The phase difference can be expressed as a path difference between the two components.

There are many types of retarders. Some common retarders are quarter-wave ($\lambda/4$) plates and half-wave ($\lambda/2$) plates. A **quarter-wave plate** is used to convert linear polarization to circular polarization and vice-versa. Recall from a previous discussion that in order to obtain circular polarization, the amplitudes of the two E vector components must be equal and their phase difference must be 90 or 270 degrees. A quarter-wave plate is capable of introducing a phase difference of 90 degrees between the two components of incident light. However, this is not enough to produce circular polarization. The direction of polarization of the incident light with respect to the optic axis of the quarter-wave plate is equally important. From Figure 4, it is obvious that the amplitudes of the two components will be equal only when the incident linear polarization direction makes an angle of 45 degrees with respect to the optic axis of the crystal (i.e. $\alpha = 45 degrees$). Figure 6 illustrates the conversion of linearly polarized light into circularly polarized light. Note that conversely, if circularly polarized light is incident on a quarter-wave plate, the resulting polarization will be linear, at an angle of 45 degrees with respect to the optic axis. Again, the reason is that a phase difference of 90 degrees is introduced between the two components of the electric field vector, which traces a helix-like path as the circularly polarized wave propagates. A **half-wave plate** functions as a polarization rotator for linearly polarized light. It rotates the polarization of a linearly polarized light by **twice** the angle between its optic axis and the initial direction of polarization, as shown in Figure 7. It introduces a phase difference of radians between the

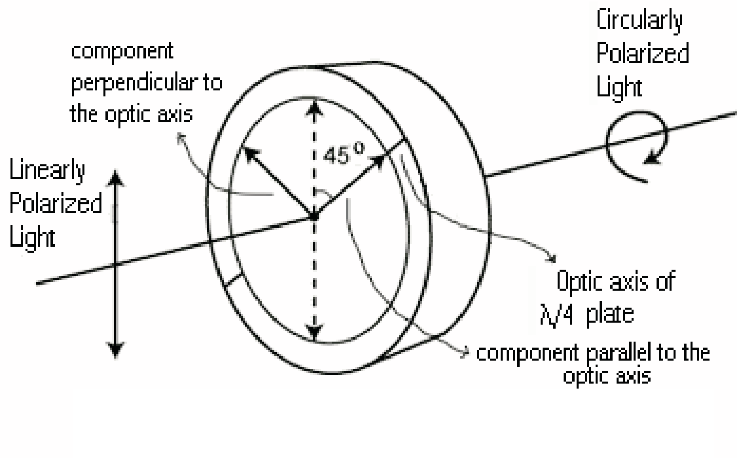

Figure 6: Conversion between linear and circular polarization by a quarter-wave plate.

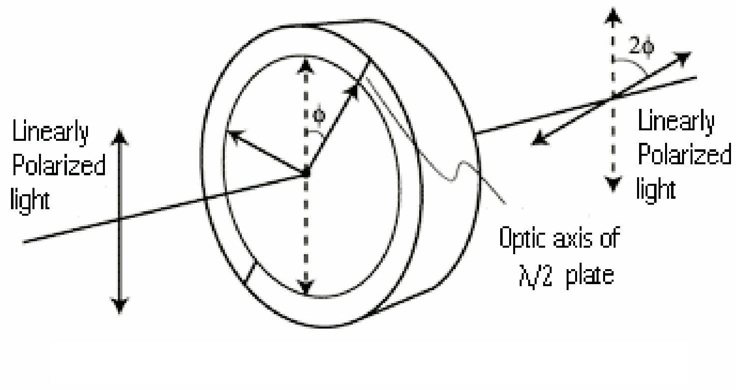

Figure 7: Rotation of linear polarization by a half-wave plate.

two components of the electric field vectors.

Neutral Density (ND) filters: Neutral density filters are used to reduce the intensity of an incident light beam. A neutral density filter has a characteristic optical density OD, related to its transmission T by the following equation,

$$OD = log_{10}(\frac{1}{T}) \tag{1}$$

Exercise 1: What optical density filter should we use if we desire to reduce the intensity of light by (i) 50% (ii) 90% (iii) 98.4%?

Linearly polarized light: Consider a source of linearly polarized light with the electric field vector E_o oscillating along the direction of polarization. Fix a frame of reference in which the x-axis is defined by the polarization direction of the light, as in Figure 8. The E_o vector oscillates along the x-axis. Suppose a polarizer is placed in front of the light source, with its transmission axis along the x'-axis making an angle α with the polarization direction of the incident light.

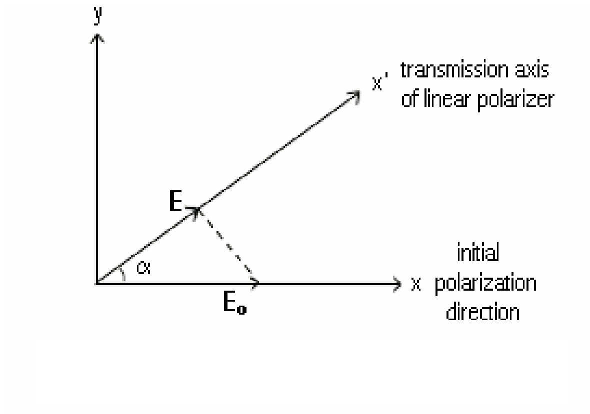

Figure 8: Transmission through linear polarizer.

Recall that only the component of the electric field vector that is along the transmission axis can pass through the polarizer. Therefore we consider the projection of E_o along the transmission axis. As light passes through the polarizer, the amplitude of the electric field vector is given by $E = E_o \cos\alpha$, figure 8. The intensity I of the light can be shown to be proportional to $|E|^2$ (refer to suggested reading). Hence, the intensity of the light after it passes through the polarizer is proportional to ${E_o}^2 \cos^2\alpha$. Equivalently, the transmitted intensity I is related to the incident intensity I_o by the following equation,

$$I = I_o \cos^2\alpha \tag{2}$$

Equation 2 is called the **transmission function** of the linear polarizer. It is obvious from equation 2 that if $\alpha = 90$ (or 270) degrees, then $I = 0$. We conclude that if the polarizer is rotated so that no light can pass through, then the polarizer's transmission axis must be perpendicular to the polarization of the incident light. On the other hand, if the transmission axis is aligned with the polarization direction, $\alpha = 0$ (or 180) degrees and the transmission is maximum ($I = I_o$).

The above analysis assumes a totally linearly polarized light source. Note that in general, the transmission function has the form,

$$I = A\cos^2\alpha + B \tag{3}$$

where A and B are constants.

Equation 2 is valid for light which is completely linearly polarized ($B = 0$ in equation 3). If unpolarized or partially polarized light is used, B will not be zero. For non-zero B, rotating the polarizer cannot completely extinguish the light.

Circular polarization: Consider the totally linearly polarized light emerging from the first linear polarizer.

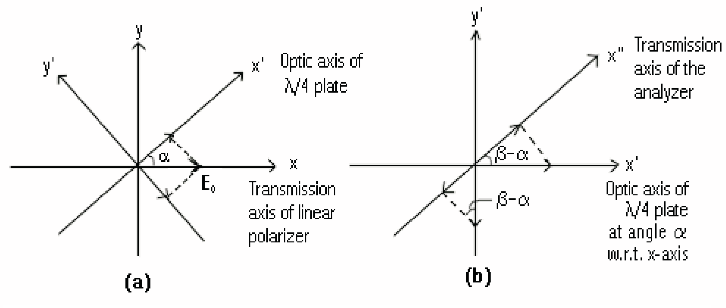

Figure 9: (a) The E vector incident on the quarter wave plate decomposes into components parallel and perpendicular to the optic axis. (b) The components along the transmission axis of the second linear polarizer are transmitted.

If a quarter-wave plate is placed between the first polarizer and the second polarizer (the analyzer), the transmission function can be derived as follows. In figure 9(a), the x-axis is along the transmission axis of the first polarizer and the x'-axis is along the optical axis of the quarter-wave plate. The angle between the x-axis and the x'-axis is α. The electric field vector along the x-axis which has an amplitude E_o can be decomposed into two orthogonal components along x' and y', having amplitudes $E_o \cos\alpha$ along x' and $-E_o \sin\alpha$ along y'. The quarter-wave retarder shifts the phase of the component along x' by $\pi/2$ radians. Assuming that the incoming light is represented in complex notation as $E_o e^{iwt}$, the components along x' and y' are,

x' axis: $E_o e^{iwt+\frac{\pi}{2}} \cos\alpha$
y' axis: $-E_o e^{iwt} \sin\alpha$

(Recall that $e^{\frac{i\pi}{2}}$ represents a $\pi/2$ phase shift and $e^{i\alpha} = cos\alpha + isin\alpha$)

Notice that the magnitude of the electric field vector that results after the quarter-wave plate is still E_o, and therefore the transmission function of the quarter-wave plate is just $I = I_o$ where I is the intensity after the quarter-wave plate and I_o is the incident intensity. In figure 9(b), the components along the x' and y' axes are projected onto the x"-axis, which represents the transmission axis of the second polarizer. The x" makes an angle β with the x-axis, or an angle $(\beta - \alpha)$ with the x'-axis. The resulting E field is,

$$E = E_o e^{iwt}(e^{\frac{i\pi}{2}} \cos\alpha . \cos(\beta - \alpha) - \sin\alpha . \sin(\beta - \alpha))$$

The intensity I of the transmitted light is proportional to $|E|^2$, $I \propto |E|^2 = E.E^*$,

$$E_o{}^2[cos(\alpha)e^{\frac{i\pi}{2}} \cos(\beta - \alpha) - \sin(\alpha).\sin(\beta - \alpha)] * [\cos(\alpha)e^{\frac{-i\pi}{2}} \cos(\beta-\alpha) - \sin(\alpha).\sin(\beta-\alpha)]$$

Here E^* is the complex conjugate of E. Further simplification yields,

$$I \propto |E|^2 = E_o{}^2[cos^2(\alpha).\cos^2(\beta-\alpha)+\sin^2(\alpha).\sin^2(\beta-\alpha)] \quad (4)$$

Exercise 2: Show that $E.E^*$ simplifies to equation 4.

Exercise 3: Show that for $\alpha = 45$ degrees,

$$I = I_o/2 \quad (5)$$

i.e. the intensity transmitted by the second polarizer is independent of the angle β.

Equation 5 is the transmission function of the second linear polarizer if circularly polarized light is incident on it. The above analysis verifies that circular polarization should be obtained by placing the optic axis of a quarter-wave plate at 45 degrees with respect to an incident linearly polarized light. We also conclude that rotating the second linear polarizer does not change the transmission of the circularly polarized light.

Rotation of polarization direction by a $\lambda/2$ plate: An analysis similar to that of the quarter-wave plate can be done to find the transmission function of a system consisting of a half-wave plate inserted between two linear polarizers.

Consider again reference frames where the x-axis is the transmission axis of the first polarizer, the x'-axis is the optic axis of the $\lambda/2$ plate making an angle α with the x-axis, and the x"-axis is the transmission axis of the second linear polarizer making an angle β with the x-axis (Figure 10).

The components along the axes x' and y' of the half-wave plate are,

x' axis: $E_o e^{iwt+\pi} \cos\alpha$
y' axis: $-E_o e^{iwt} \sin\alpha$

Therefore, as in the case of a quarter-wave plate, the transmission function of the half-wave plate is $I = I_o$. Again, this reflects the fact that retarders do not reduce the intensity of incident light.

We proceed to derive the transmission function of the whole system. The E-field along the x" axis is,

$$E = E_o e^{iwt}(e^{i\pi}\cos\alpha.\cos(\beta-\alpha) - \sin\alpha.\sin(\beta-\alpha))$$

Keep in mind that a half wave plate introduces a phase shift of π radians between the two components of the E vector.

The intensity I of the transmitted light being proportional to $|E|^2$, we have,

$I \propto |E|^2 = E.E^*$

$= {E_o}^2[\cos^2\alpha.\cos^2(\beta-\alpha) + \sin^2\alpha.\sin^2(\beta-\alpha) - \cos\alpha.\cos(\beta-\alpha).\sin\alpha.\sin(\beta-\alpha)(e^{i\pi}+e^{-i\pi})$

$= {E_o}^2[cos\alpha.\cos(\beta-\alpha)+\sin\alpha.\sin(\beta-\alpha)]^2$

Since $(e^{i\pi}+e^{-i\pi}) = 2\cos\pi = -2$,

$$I = I_o[cos\alpha.\cos(\beta-\alpha)+\sin\alpha.\sin(\beta-\alpha)]^2 \qquad (6)$$

Equation 6 is the transmission function of the system (consisting of the first linear polarizer, $\lambda/2$ plate and the second linear polarizer) for arbitrary angles α and β.

Exercise 4a: What is the transmission function through the second linear polarizer for each of the following cases,

1. The optic axis of the $\lambda/2$ plate is aligned with the transmission axis of the first polarizer.
2. The optic axis of the $\lambda/2$ plate is at 45 degrees with respect to the transmission axis of the first linear polarizer.

Exercise 4b: Deduce the type of polarization the $\lambda/2$ plate produces in each case.
Exercise 4c: Is the polarization direction rotated in any of the above cases? Why? (Recall a previous discussion on $\lambda/2$ retarders).

Now consider the case where the optic axis of the $\lambda/2$ plate is at 45 degrees with respect to the transmission axis of the first linear polarizer. Substituting $\alpha = \pi/4$ radians in equation 6 we get,

$I = \frac{1}{2}I_o[1+2\cos(\beta-\frac{\pi}{4}).\sin(\beta-\frac{\pi}{4})]$

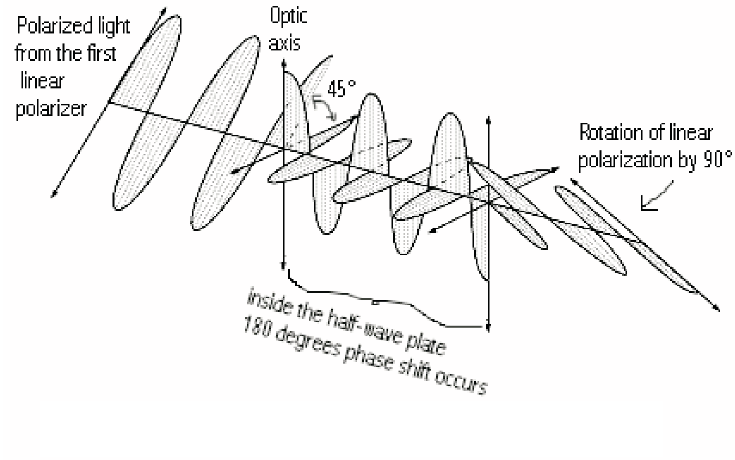

Figure 10: 90^o rotation of the polarization direction by a half-wave plate due to the phase difference between the E field components.

Using $\sin(2a) = 2sin(a)cos(a)$,

$I = \frac{1}{2}I_o[1+\sin(2\beta-\frac{\pi}{2})]$

Since $\sin(a-\frac{\pi}{2}) = -cos(a)$,

$I = \frac{1}{2}I_o[1-\cos(2\beta)]$

Using $\cos(2a) = 2\cos^2(a)-1$,

$I = \frac{1}{2}I_o[2-2\cos^2(\beta)] = I_o[1-\cos^2(\beta)]$

Finally,

$$I = I_o\sin^2(\beta) \qquad (7)$$

Comparing equation 7 with equation 2 (which is the transmission function obtained in the absence of the $\lambda/2$ plate), notice that the transmission function of equation 7 is 90 degrees out of phase with respect to that of equation 2. This indicates that the $\lambda/2$ plate has produced linearly polarized light which is rotated 90 degrees with respect to the incident polarization direction. This is illustrated in Figure 10. **Exercise 5:** Prove that in general for any arbitrary angle α, a half-wave plate rotates the polarization direction by 2α as in Figure 7. (Hint: substitute an appropriate value for β in equation 6).

3 Suggested Reading

Refer to the chapter on Polarization,

D. Halliday, R. Resnick and K. S. Krane, **Physics** (Volume 2, 5th Edition, John Wiley, 2002)

Check out the website http://www.polarization.com.

4 Apparatus

- He-Ne laser (633nm)
- Firm base for the laser
- Neutral density filters: 0.3, 1.0 and 1.8 with frames and posts
- Square mount, clamp and post for the ND 1.8 filter
- Two linear polarizers attached to graduated rotatable frames and posts
- Two quarter wave ($\lambda/4$) plates attached to rotatable frames and posts
- Linear polarizer attached to a motor
- Holder for the motor
- Battery for the motor
- Photodiode
- Voltmeter
- Oscilloscope
- Banana/BNC connectors for the photodiode, voltmeter and scope
- Seven bases and postholders for the filter, polarizing sheets and photodiode
- Screws, bolts, 3/16" Allen key, cardboards, transparent lens paper
- ND filters posts
- Optical table

NOTE: It is crucial to read the whole lab report and understand it before attempting to do the experiments.

WARNING!!: KEEP TRACK OF YOUR LASER BEAM AT ALL TIMES. NEVER POINT THE BEAM AT PEOPLE, OR LOOK IN THE APERTURE OF THE LASER OR BE AT EYELEVEL WITH THE BEAM. KEEP EYES AWAY FROM DIRECT OR REFLECTED LASER BEAMS. OTHERWISE SERIOUS EYE DAMAGE WILL OCCUR.

YOU SHOULD BE AWARE OF WHERE THE LASER BEAMS STRIKE OPTICAL COMPONENTS. REFLECTIONS FROM OPTICAL COMPONENTS SHOULD BE BLOCKED BY USING PIECES OF CARDBOARD THAT ARE PROVIDED. BE PARTICULARLY CAREFUL WHEN YOU INSERT OR REMOVE LENSES INTO A LASER BEAM.

DO NOT TOUCH THE OPTICAL SURFACES OF LENSES AND MIRRORS. IF THE SURFACES ARE UNCLEAN, PLEASE BRING IT TO THE ATTENTION OF THE TA IMMEDIATELY.

USE THE TRANSPARENT LENS TISSUES TO DETECT THE BEAMS.

MAKE SURE ALL MOUNTS ARE SECURELY FASTENED ON THE OPTICAL TABLE.

5 Experiment I: Linearly polarized light

You will use a He-Ne laser which has a wavelength of 633nm. The light produced by the He-Ne laser may not be completely polarized. The purpose of this first experiment is to check the polarization state of the laser and define its polarization direction. To accomplish this, you will measure the transmission of the light through a linear polarizer as its transmission axis is rotated. The intensity of the transmitted light can be measured by a photodiode connected to a voltmeter or to an oscilloscope. The voltmeter reading is proportional to the intensity of the light that hits the photodiode. Knowing the transmission function, you will be able to deduce whether the laser light is completely linearly polarized or partially polarized.

The experimental setup is as shown in figure 11. First, fix the base of the laser firmly on the optical table. Mount the laser horizontally. The laser beam should be horizontal and it should have the same height everywhere. Check this by marking the height of the

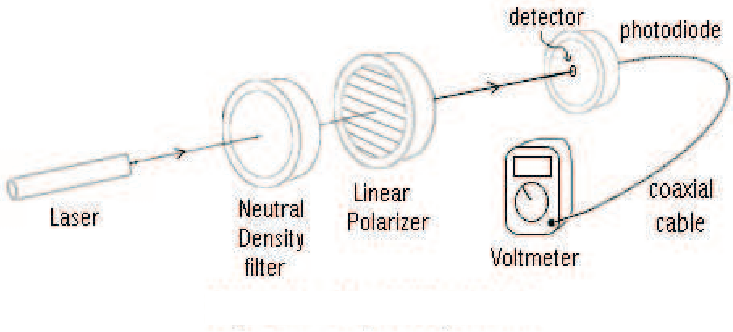

Figure 11: Setup for experiment 1.

beam on a piece of cardboard. Before turning on the laser, fix the photodiode on the table. Make sure you leave enough space between the laser and the photodiode, since you will be adding other optical components in between during subsequent experiments. Connect the photodiode to the voltmeter. Turn the laser on and make sure the beam hits the detector at the center of the photodiode. It is helpful to align the laser beam along one of the rows of threaded holes on the optical table.

Turn on the photodiode. If the light incident on the photodiode is too intense, the photodiode becomes insensitive to small changes in the intensity of the light and the voltmeter reading remains fixed. In this situation, the photodiode is said to be **saturated**. To avoid the saturation of the photodiode, use a neutral density filter of OD=1.0 to reduce the intensity of the laser beam. Throughout the experiments, you should occasionally test whether the photodiode is saturated, by holding an OD=0.3 ND filter in front of the photodiode. If the voltmeter reading is reduced by 50%, the photodiode is not saturated. If the voltmeter reading is unchanged, then you should further reduce the intensity of the laser beam by using a second ND filter (such as ND 1.8).

Finally, position the linear polarizer as shown in Figure 11. Rotate the ND filter(s) and the polarizer such that the beam is perpendicular to all the optical surfaces and passes through the centers of all the optical devices. Make sure that the polarizer is oriented perpendicular to the beam. Block unnecessary reflections. Whenever you add an optical component, make sure that the laser beam still hits the detector at the center of the photodiode.

Note: The transmission axis of each polarizer is parallel to the cut edge.

Exercise 6a: Turn the photodiode on and record the voltmeter readings as you rotate the polarizer by increments of 30 degrees. (Remember to make sure that the photodiode does not saturate).
Exercise 6b: Record the voltmeter reading while blocking the laser beam. This is the background signal that must be subtracted from your data.
Exercise 6c: Plot your data. Does the transmitted intensity ever go to zero? What does this tell you about the laser's polarization?
Exercise 6d: Adjust the polarizer so that the voltmeter reading is at its maximum. Record the angle of the polarizer's transmission axis with respect to the vertical direction. Sketch a picture to indicate the direction of polarization (with respect to the vertical) of the transmitted light.

6 Experiment II: Analysis of totally linearly polarized light

Having defined the laser's polarization direction with a linear polarizer in experiment 1, you will now study the properties of linearly polarized light.

Place the second linear polarizer, usually referred to as an **analyzer**, between the first polarizer and the photodiode. Note that you may not need to use the OD=1.8 ND filter in this and in the following parts of the experiment (adding a second polarizer reduces the intensity of the beam).

Exercise 7a: Rotate the second polarizer (while keeping the first polarizer fixed at the angle determined in experiment 1) and record voltmeter readings every 30 degrees.
Exercise 7b: Subtract the background signal from your data.
Exercise 7c: Plot a graph of the transmitted intensity against the angle between the transmission axes of the first and the second polarizers.
Exercise 7d: How do your results compare with experiment 1? Interpret.

7 Experiment III: Circular polarization

The purpose of this part of the experiment is to verify that circular polarization is obtained whenever the quarter wave plate axis is at 45 degrees with respect to the incident linear polarization.

Keep the first linear polarizer fixed at the angle determined in experiment 1. Remove the second linear polarizer and put in a $\lambda/4$ plate between the first linear polarizer and the photodiode. Instead of using the second linear polarizer and rotating it by hand, you will use a linear polarizer attached to a motor, so that you will be able to observe the photodiode signal on the oscilloscope and determine the angle of the axis of the quarter wave plate at which circular polarization is obtained. Place the linear polarizer attached to the motor behind the $\lambda/4$ plate. Connect the photodiode output to channel 1 of the oscilloscope and make sure the light reaches the photodiode without being blocked by the motor. Turn the motor and the oscilloscope on and set the trigger source to channel 1. Adjust the trigger level to find the signal on the oscilloscope. You may also need to adjust the horizontal and vertical sensitivity of the oscilloscope.

Exercise 8a: Once the signal is located, slowly rotate the quarter-wave plate and observe the signal on the oscilloscope. Explain your observations.
Exercise 8b: Rotate the $\lambda/4$ plate until the maximum peak-to-peak amplitude is observed. Record the maximum amplitude of the signal and make a sketch of the observed signal. What is the polarization of light after the waveplate?
Exercise 8c: Next, rotate the $\lambda/4$ plate to minimize the amplitude of the signal. Ideally the minimum would be a straight line, which indicates circularly polarized light. However, in practice, pure circular polarization is hard to achieve. Record the minimum amplitude of the signal and sketch the oscilloscope signal on the same sketch for the maximum amplitude waveform you sketched in exercise 8b. Also, record the corresponding angle α that you have rotated the waveplate through. Does this angle correspond to the theoretical prediction?
Exercise 8d: From the minimum amplitude A_{min} and maximum amplitude A_{max} calculate the percentage of circular polarization,

$$\% \text{ of circular polarization} = \frac{A_{max}-A_{min}}{A_{max}} \times 100\%$$

Replace the motor by a regular linear polarizer. Align both the axes of the second linear polarizer and the $\lambda/4$ plate with the axis of the first polarizer. Verify that the reading on the voltmeter (or the oscilloscope signal) is at maximum.

Exercise 9a: Rotate the $\lambda/4$ plate by 90 degrees. Does the voltmeter reading change? What does this tell you about the polarization of light transmitted through a $\lambda/4$ plate at (i) 0 degrees and (ii) 90 degrees with respect to the transmission axis of the linear polarizers?
Exercise 9b: Explain your observations by substituting (i) $\beta = 0$ and $\alpha = 0$ and (ii) $\beta = 0$ and $\alpha = 90$ degrees in equation!4.

8 Experiment IV: Rotation of polarization direction by a $\lambda/2$ plate.

In this experiment, two quarter-wave plates are used to create a half-wave plate and observe its properties.

A half-wave plate can be constructed from two quarter-wave plates with their axes aligned, resulting in a phase shift of π radians in one of the components of the E-vector.

Setup the polarizers and $\lambda/4$ plates as shown in Figure 12. You will use the voltmeter in this part of the experiment. Place **both** $\lambda/4$ plates at 45 degrees with respect to the axis of the **first** linear polarizer.

Rotate the second linear polarizer by increments of 30 degrees and record the voltmeter readings. Subtract the background signal from your data.

Exercise 10a: Plot a graph of the voltage readings vs. the angle of the second polarizer with respect to the first polarizer. Compare this plot with the plot obtained in exercise 7(c) of experiment 1. What is the phase shift between the two graphs? Does this agree with theory?
Exercise 10b: Draw Figure 12 and indicate the type and direction of polarization that occurs at every stage as light travels through each optical element (for the case where the $\lambda/4$ plates are both at 45 degrees with respect to the first polarizer).

Now place the axes of both $\lambda/4$ plates at 0 degrees with respect to the first polarizer.

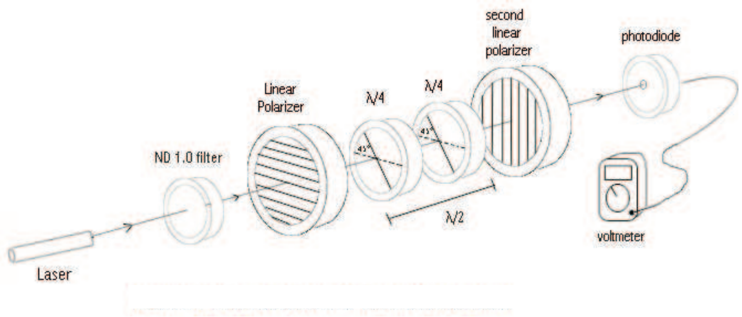

Figure 12: Setup for experiment 4, 90^o rotation of linear polarization.

Exercise 11a: What is the type and the direction of polarization that results?
Exercise 11b: Next, place the axes of both $\lambda/4$ plates at 90 degrees with respect to the first polarizer. What is the type and the direction of polarization that results? Do these agree with your answers to exercise 4?
Exercise 11c: Keeping the first $\lambda/4$ plate at 45 degrees with respect to the first linear polarizer, what happens if you place the second $\lambda/4$ plate at 0 degrees with respect to the first linear polarizer? At 90 degrees with respect to the first linear polarizer? Explain. (Note that the two $\lambda/4$ plates do not constitute a $\lambda/2$ plate whenever their axes are not aligned).

Note: Once you have completed the experiment, please remove all optical elements and the detector from their mounts and place them on the optical table.

Your lab report should include:

Answers to exercises 1-11 with relevant data tables, graphs, figures and qualitative comments.

Refer to Appendix C for Maple worksheets.