POLARIZATION

Before beginning this lab, read Chapter 24 of Jenkins and White – Fundamentals of Physical Optics.

The direction of polarization of an electromagnetic wave is defined to be the direction in which the electric field vector ($\vec{E}$) points. Since EM waves are transverse, the $\vec{E}$ vector always points in a direction which is perpendicular to the direction of propagation. If the direction of the $\vec{E}$ vector is constant in time, the wave is called linearly polarized. For a wave propagating in the $\hat{z}$ direction, the $\vec{E}$ vector of a linearly polarized plane wave of angular frequency ω can be written as:

$$\vec{E}(z,t) = \mathrm{Re}\left(E_{0x}\hat{x} + E_{0y}\hat{y}\right)e^{i(kz-\omega t)}. \qquad (1)$$

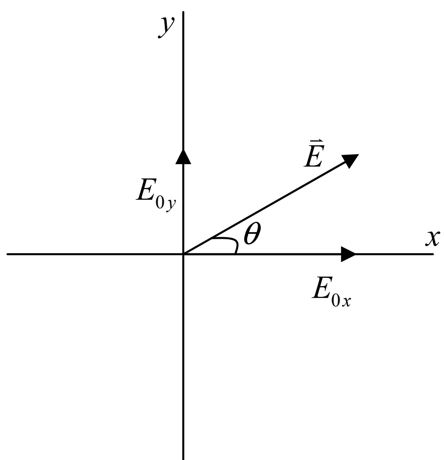

Fig. 1

The amplitude of this $\vec{E}$ vector oscillates in time, but the direction is always the same if E_{0x} and E_{0y} are both real (see Fig. 1). The angle θ, which $\vec{E}$ makes with the $\hat{x}$ axis, is given by $\tan\theta = E_{0y}/E_{0x}$.

In the general case, there may also be a phase difference between the x and y components of $\vec{E}$. One way to describe such a wave is with an expression of the form:

$$\vec{E}(z,t) = \mathrm{Re}\left(E_{0x}\hat{x} + iE_{0y}\hat{y}\right)e^{i(kz-\omega t)}. \qquad (2)$$

If we first consider the case where $E_{0x} = E_{0y}$, then this wave would be called circularly polarized. The x and y components are equal in magnitude, but 90° out of phase. This results in an $\vec{E}$ field whose amplitude is constant in time, but whose direction is rotating clockwise in a circle (when viewed head on) at a frequency ω. Such a wave is called right circularly polarized.

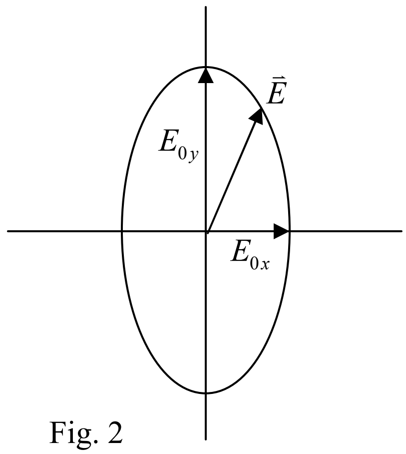

Fig. 2

In the more general case where $|E_{0x}| \neq |E_{0y}|$, the $\vec{E}$ field amplitude is not constant in time. Instead, the tip of the $\vec{E}$ vector traces out an ellipse (see Fig. 2) whose major and minor axes are given by E_{0x} and E_{0y}. Such a wave is called elliptically polarized.

In this experiment, you will use various linear polarizers and wave plates, in combination with a laser, to study the properties of polarized light and the various polarizing elements.

It is possible to produce linearly polarized light by reflecting the light from any nearly monochromatic source from a glass plate, with the angle of incidence set to Brewster's angle θ_B. When light from an unpolarized or partially polarized source strikes a plane interface at an angle of incidence equal to θ_B, the component of the light polarized in the plane of incidence (i.e. in the plane containing the incident, transmitted, and reflected waves) is completely transmitted, while the component perpendicular to the plane of incidence is partially transmitted and partially reflected. Thus the reflected light is 100% plane polarized in a direction perpendicular to the plane of incidence. Brewster's angle is determined from the expression $\theta_B + \theta_2 = 90^{\circ}$ (see Fig. 3). Using Snell's law, this reduces to:

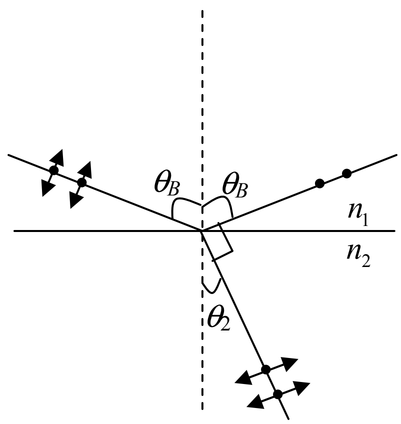

Fig. 3

$$\tan\theta_B = \frac{n_2}{n_1}. \qquad (3)$$

A second method to create polarized light is to send it through a prism polarizer such as a Nicol prism. The Nicol prism is described in Jenkins and White, p. 500-502, but for the purposes of this lab we may think of it as a simple linear polarizer. The Nicol prism passes only the component of the incident light which is polarized along its transmission axis.

Finally, you will be using and studying the properties of birefringent retardation plates. In birefringent materials there exists a particular direction called the optic axis. Light polarized perpendicular to the optic axis moves with a velocity $v_o = c/n_o$ characterized by the "ordinary"

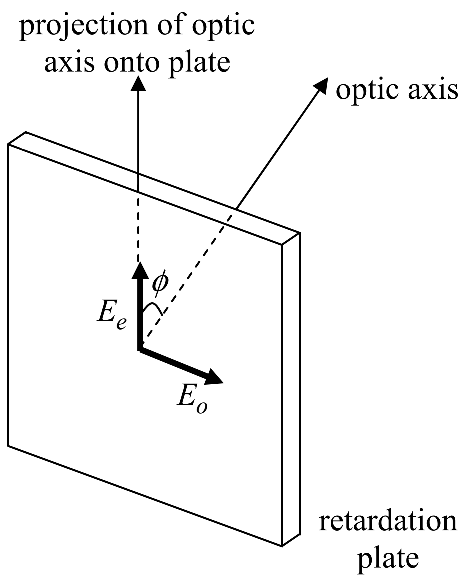

Fig. 4

index of refraction n_o. Light whose polarization vector is perpendicular to that of the ordinary ray will have a component of its $\vec{E}$ vector along the optic axis (see Fig. 4). This "extraordinarily ray" will propogate with velocity $v_e = c/n_e$. Note that although n_e is a function of ϕ, which is the angle between the optic axis and the plane of polarization, it is a constant for a given retardation plate. Since the ordinary and extraordinary rays travel with different velocities, their relative phase will change as they propogate. In particular, if the thickness of the plate, *d*, is such that

$$(n_o - n_e)d = (m + \frac{1}{4})\,\lambda_{vac} \tag{4}$$

then the plate is called a λ/4 plate. Such a plate can be used to convert linearly polarized light into circularly polarized light. In a similar fashion, a λ/2 plate, described by

$$(n_o - n_e)d = (m + \frac{1}{2})\,\lambda_{vac} \tag{5}$$

can be used to rotate the polarization direction of linearly polarized light.

The Experiment

1) From the definition $\theta_B + \theta_2 = 90^\circ$ and Snell's Law, derive Eq. (3). Use the apparatus to find Brewster's angle for a glass plate, and thereby find the index of refraction of the particular glass you are using.

2) Starting from Eqs. (4) and (5) and the phase of the linearly polarized light described by Eq. (1), prove that a λ/4 plate can be used to convert linearly polarized light into circularly polarized light, and that a λ/2 plate can be used to rotate the polarization direction of linearly polarized light. Note that inside the wave plate $k = 2\pi/\lambda$ depends on polarization, i.e. $\vec{E} = \mathrm{Re}\left[E_{ox}\hat{e}_x e^{ikz - i\omega t} + E_{oy}\hat{e}_y e^{ik'z - i\omega t} \right]$. Predict theoretically the effect of various types of retardation plates for various orientations of the plate axes with the direction of polarization.

3) Use your predictions of the effects of various type retardation plates on plane polarized light to devise tests for a λ/2 and λ/4 plate.

4) Test at least 3 of the unknown retardation plates (be sure to record their stock numbers in your lab book) and one of the official 633 nm λ/4 plates to determine whether each is λ/2, λ/4 or "other" for light of wavelength 633 nm. By other, we mean the plate can be described by

$$(n_o - n_e)d = (m + \frac{1}{x})\,\lambda_{vac} \qquad (6)$$

Such a plate could be called λ/*x*, although *x* may not be an integer.

5) For one of the plates called "other", devise a measurement procedure using a known λ/4 plate and your analyzer (linear polarizer) to determine quantitatively the retardation of that plate for 633 nm light. Carry out this procedure.

Hint for task #5:

1) Set up the analyzer with a linearly polarized source, and rotate until extinction occurs.
2) Insert a λ/4 plate between source and analyzer and rotate until extinction occurs. This aligns either the fast or the slow axis of the λ/4 plate with the source polarization direction.
3) Insert the unknown between the source and the λ/4 plate, and rotate until extinction occurs. This aligns either the fast or the slow axis of the unknown with the source polarization direction.

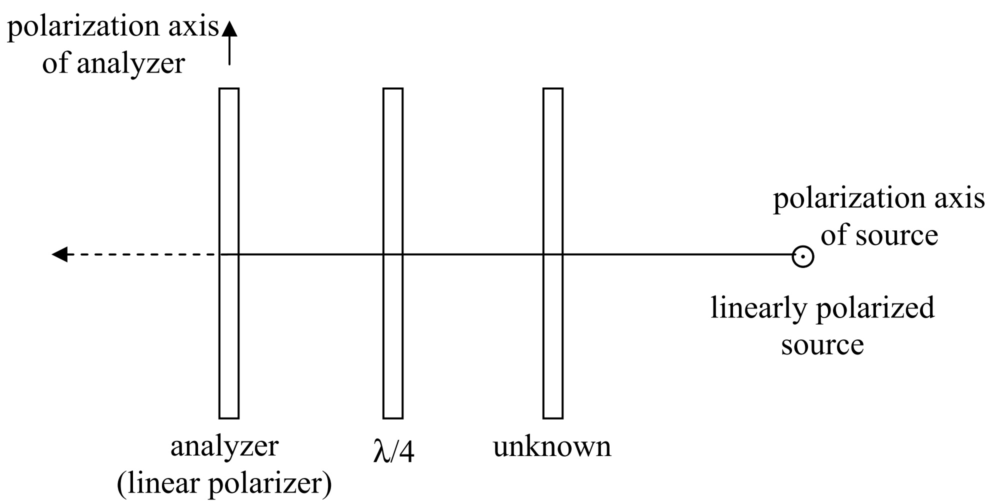

Fig. 5

4) Rotate the unknown 45^o so that the ordinary and extraordinary rays have equal amplitudes. Light emerging from the unknown will then be elliptically polarized with the major and minor axes of the ellipse oriented parallel and perpendicular to the source polarization direction. [You must prove this last statement, that light emerging from the unknown in this final configuration is elliptically polarized with the major and minor axes of the ellipse oriented parallel and perpendicular to the source polarization direction.]
5) The elliptically polarized light is now incident on the $\lambda/4$ plate whose axes are oriented parallel and perpendicular to the source polarization direction. The effect of the $\lambda/4$ plate is to introduce a phase change of $\pi/2$ between the two components, thereby bringing them

back into phase. Therefore, the polarization emerging from the $\lambda/4$ plate is linear. The linear polarization direction makes an angle $\varphi = \pi\delta/\lambda$ with respect to the source polarization. [You need to prove this.] Therefore, by measuring the rotation angle φ, one can obtain the retardation δ. How does δ relate to x in Eq. (6)?