# Polarization of Light

**Apparatus:**
Laser source, optical bench or bread board, polarizers with mount, photodetector, prism mounted on rotating table.

**Basic methodology:** The incident light is passed through polarizers at varying angles to each other and the state of polarization can be determined.

## I Theory:

Classically, light in oscillations in electric and magnetic fields. These oscillations travel as a wave, in which the directions of oscillations of the electric and magnetic fields are transverse to the direction of propagation of light. This is similar to the oscillations of a vibrating string, but in contrast to sound waves, in which the material particles of the medium oscillate along the same direction as that of propagation (longitudinal).

Natural sources of light do not prefer any particular direction, and light is emitted in wave-trains of random polarization. Such light is naturally unpolarized. The electric field vector direction could be selected by various processes, and give rise to polarized light. The simplest choice is a single direction in the polarization plane. This is called linear polarization. Commercial polaroid filters, for instance, polarize incident light along a direction known as their pass axis. This axis is determined by the orientation of polymer chains that these materials are constituted out of. Figure 1 indicates linearly polarized light.

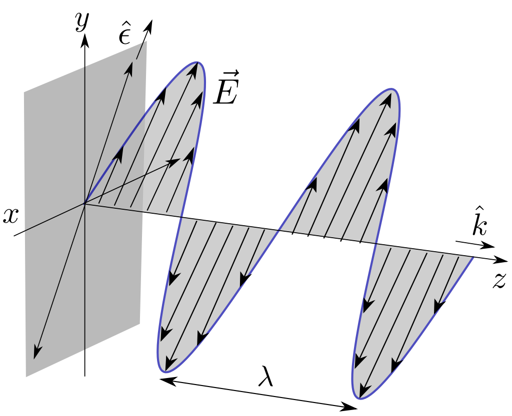


Figure 1: Linearly polarized light wave

The important parameters that describe a monochromatic light wave are its wavelength $\lambda$, angular frequency (colour) $\omega$ and the wave vector $\vec{\boldsymbol{k}} = \frac{2\pi}{\lambda}\hat{\boldsymbol{k}}$ giving the direction of propagation. The direction $\hat{\boldsymbol{k}}$ is conventionally taken to be $\hat{\boldsymbol{z}}$. The electric field vector then looks like

$$\overrightarrow{\boldsymbol{E}} \quad = \quad E_0 \hat{\boldsymbol{\epsilon}} \cos(kz - \omega t). \tag{1}$$

In general, the electric field vector could rotate in the $x$-$y$ plane as the wave propagates. This situation is described as elliptic polarization. The field vector rotates in a clockwise or anticlockwise direction, and can also change in magnitude. If the magnitude remains unchanged, then we have right- or left- circular polarization. One can define the polarization vector by

$$\hat{\boldsymbol{\epsilon}} = \frac{E_x}{|\overrightarrow{\boldsymbol{E}}|}\hat{\boldsymbol{x}} + \frac{E_y}{|\overrightarrow{\boldsymbol{E}}|} e^{i\phi} \hat{\boldsymbol{y}}. \tag{2}$$

This is in general elliptical polarization. The special case $\phi = \pi/2$ corresponds to circular polarization while $\phi = 0$ is linear polarization.

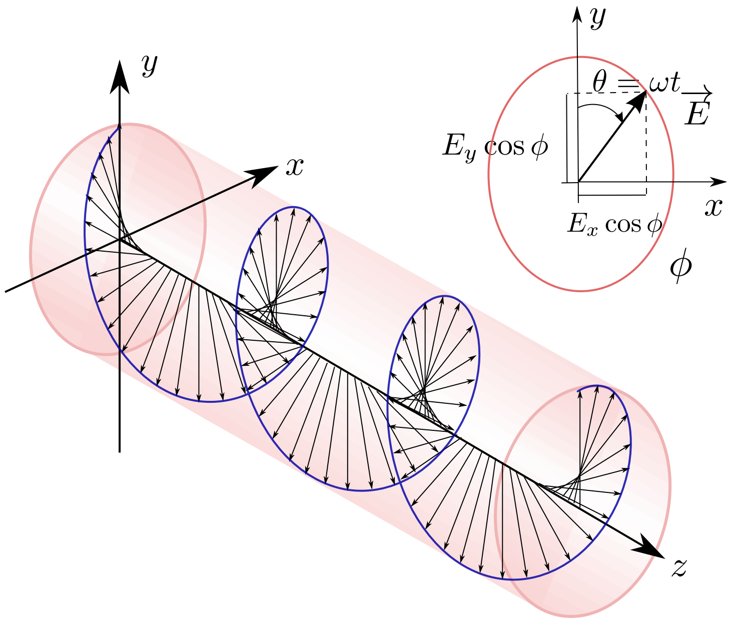


Figure 2: General elliptically polarized light

## I.1 Linear Polarizers: Malus' Law

When unpolarized light is incident on a linear polarizer, then only the component of the electric field parallel to its pass axis is transmitted. The intensity of the transmitted light can be detected by a photodetector, which responds to the electric field of the light, say $E_0$, and measures its amplitude squared. Let this intensity be $|E_0|^2 = I_0$. We can now use a second identical polarizer in the path of the transmitted light, to determine the direction of the pass axis.

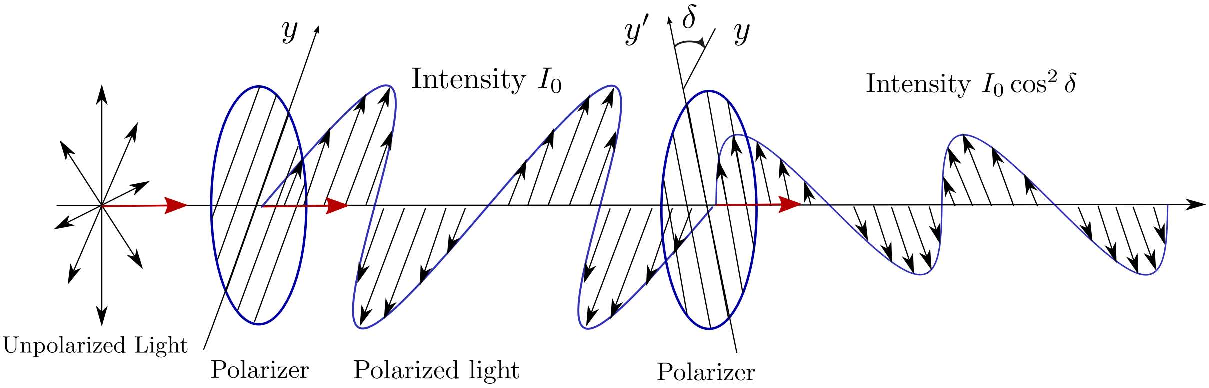


Figure 3: Malus' Law

This polarizer will be called the "analyzer". As we rotate the analyzer about the $z$ axis, when the pass axis of the analyzer makes an angle $\delta$ with that of the original polarizer, then only a component $E_0 \cos\delta$ that is parallel to the analyzer pass axis is further transmitted.

If we now place a photodetector on the path of the transmitted light, it will record an intensity

$$I = I_0 \cos^2 \delta. \tag{3}$$

This result is often called Malus' law, after a French engineer in Napoleon's army, named Etienne Malus, who first published it in 1807. Note that when $\delta = \pi/2$, the transmitted intensity is zero. The two polarizers are then said to be crossed. You can thus use Malus' law to verify whether a given optical element is a linear polarizer or not. You can also determine its pass axis.

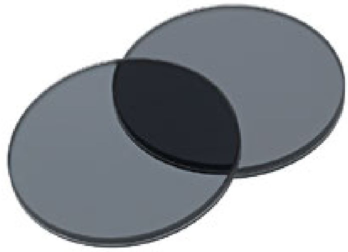

Figure 4: Crossed polarizers

## I.2 Polarization by Reflection: Brewster's Angle

One of the most common natural sources of polarization is by reflection on a dielectric surface. One of Richard Feynman's favorite teaching exercises was to hand out polaroid filters to a class and ask them to look at the surface of the sea through them. At a particular angle, the light from the sea surface is extinguished! This phenomenon was also first recorded by E Malus, who was looking at the reflection of the setting sun on a window pane, through a calcite crystal (which produces two beams of opposite polarizations, and hence a double image). At a particular angle he found that one of the double images vanished.

The reason this happens can be understood by applying the boundary conditions at a dielectric surface to the electric field of the incident light. Consider an electromagnetic wave incident at angle $\theta_i$ on a glass surface. The wave is refracted at the interface, transmitted at an angle $\theta_t$. Some of the light is reflected from the surface at angle $\theta_r$. The fraction of intensity of the reflected wave depends on the polarization of the incident light.

The reflectance, defined as the ratio of reflected intensity to incident intensity is different for the component of the electric field perpendicular to the plane of incidence, and that parallel to the plane of incidence:

$$R_\perp = \frac{\sin^2(\theta_i - \theta_t)}{\sin^2(\theta_i + \theta_t)}, \tag{4}$$

$$R_{||} = \frac{\tan^2(\theta_i - \theta_t)}{\tan^2(\theta_i + \theta_t)} \tag{5}$$

These relations can be derived from wave theory, from what are called the Fresnel equations. Notice that while $R_\perp$ can never be zero, $R_{||}$ can be zero when the denominator is infinite, i.e. when $\theta_i + \theta_t = \pi/2$. When this condition is met, the component of the E-field parallel to the plane on incidence vanishes, and the reflected light is totally polarized perpendicular to the plane of incidence (parallel to the surface). This phenomenon is called Brewster's law, and the angle of incidence at which this occurs is known as **Brewster's angle**, $\theta_p$. This angle can be calculated using Snell's law, $n_i \sin\theta_p = n_t \sin\theta_t$. Using $\theta_t = \pi/2 - \theta_p$, we have

$$\tan\theta_p = \frac{n_t}{n_i}. \tag{6}$$

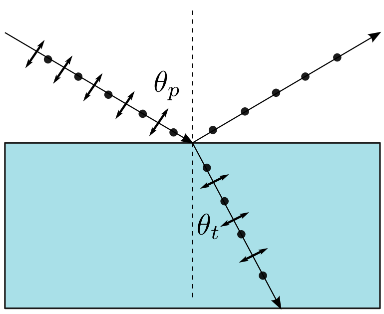


Figure 5: Polarization at Brewster's Angle

# II Set-up and Procedure:

A. Verify that the polarizers given to you are linear.

1. Align the laser beam, polarizer, analyzer and detector to the same height.
2. Experiment by rotating the analyzer to find the position where the intensity is maximum. At this position, the two polarizers have their pass axes parallel.
3. Rotate the analyzer in steps of 5°, and record the intensity as a function of angle $\delta$ between polarizer and analyzer.
4. Plot a graph of intensity vs $\cos^2\delta$ and verify Malus' law.

B. Check if the incident laser light is itself linearly polarized.
Use a single polarizer to analyze the light and draw your own conclusions.

C. Brewster's Law

1. Mount The glass plate on the rotating platform and swing it around to ensure that the reflected beam is at the same height throughout.
2. Check that at zero angle of incidence, the reflected beam returns along the incident path. Note the angle reading on the scale: this is the reference position for zero.
3. Mount a polarizer between the plate and the source, and measure the intensity of the direct beam, $I_0$.
4. Adjust the polarizer to get polarization perpendicular to the plane of incidence.
5. Measure the intensity of the reflected beam at 5°intervals of angle of incidence.
6. Determine the direction of polarization of the reflected light.
7. Repeat for polarization parallel to the plane of incidence.
8. Plot reflectance vs incidence angle for each polarization.
9. Deduce Brewster's angle from your graph and compare with the calculated value.
10. Remove the polarizer, and verify that the reflected light at Brewster's angle is totally polarized.
11. Verify that when the incident light is polarized parallel to the incidence plane, there is no reflected light at Brewster's angle.

***Precautions:***

1. *The optical elements must be aligned carefully to be centered at the same height*
2. *The surface of the polaroid filters should not be touched.*
3. *When light intensity readings are taken, background light should be reduced to a minimum.*

# III Exercises and Viva Questions

1. Suppose we write the polarization vector as

$$\vec{\boldsymbol{\epsilon}} = \frac{E_x}{|\overrightarrow{\boldsymbol{E}}|}\left(\hat{\boldsymbol{x}} + ae^{i\phi}\hat{\boldsymbol{y}}\right).$$

   What kind of polarization do the following correspond to? Indicate with a diagram.

   (a) $\phi = 0, a = 1$

   (b) $\phi = 0, a = 2$

   (c) $\phi = \pi/2, a = -1$

   (d) $\phi = \pi/4, a = 1$.

2. Linearly polarized light with its electric field at 40 deg in incident on an linear polarizer whose pass axis is at 10 deg to the vertical. Another linear polarizer is placed behind this, with its pass a axis at 60 deg to the vertical. What fraction of the incident intensity ?

3. Natural light of intensity $1000W/m$ is incident on a linear polarizer with pass axis at 0 deg to the vertical. Behind this is placed another polarizer with pass axis at 50 deg to the vertical. What is the intensity of the emergent light? Now if a third polarizer is placed *between* the first two polarizers, with its pass axis at 25 deg, what is the intensity of the emergent light?

4. A beam of intensity $I_0$ emerges from a polarizer with intensity $I_1$. Another polarizer is placed with its axis crossing the first. If now another polarizer in introduced between these two, with its axis at 45 deg, what is the intensity of the emergent light?

5. Sea water has refractive index 1.35. At what angle will sky light reflected from the sea surface completely vanish when viewed through a polaroid filter?

## References:

1. “Optics” by Eugene Hecht, 4th edition, Addison Wesley