Chapter Six

Polarization

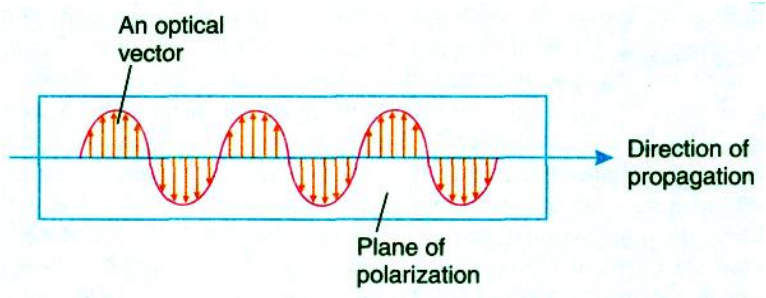
6.1 Introduction

Interference and diffraction phenomena proved that light a wave motion and enabled the determination of the wavelength. However, they do not give any indication regarding the character of the waves. Whether the light waves are longitudinal or transverse, or whether the vibrations are linear or circular cannot be deduced from the above two phenomena, as all kinds of waves under suitable conditions exhibit interference and diffraction. In 1816 Arago and Fresnel showed that light waves vibrating in mutually perpendicular planes do not interfere. In 1817 Thomas Young explained the absence of interference by postulating that light waves are ***transverse waves***. About fifty years later, Maxwell developed electromagnetic theory and suggested that light waves are electromagnetic waves. As electromagnetic waves are transverse waves, it is obvious that light waves too are transverse waves. The concept of transverse nature leads to the concept of polarization. The state of polarization cannot be detected by unaided human eye. An understanding of polarization is essential for understanding the propagation of electromagnetic waves guided through wave-guides and optical fibers. Polarized light has many important applications in industry and engineering. One of the most important applications is in liquid crystal displays (LCDs) which are widely used in wristwatches, calculators, TV screens etc.

6.2 Preferential Direction in a Wave

Waves are basically of two types, namely longitudinal waves and transverse waves. A wave in which particles of medium oscillate *to and fro* along the direction of wave propagation is called a **longitudinal wave.** Sound waves and waves produced on a spring are examples of longitudinal waves. The longitudinal waves consist of alternate compressions and rarefactions.

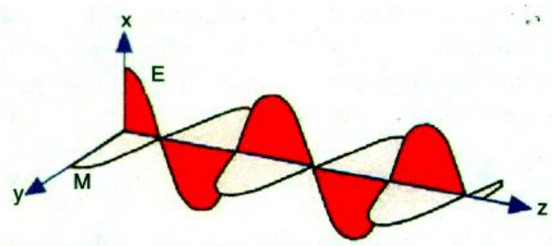
A wave in which every particle of the medium oscillates ***up and down*** at right angles to the direction of wave propagation is called a transverse wave. In a transverse wave, the direction of particle displacement occur perpendicular to the wave propagation.



An electromagnetic wave is a transverse wave consisting of electric and magnetic fields vibrating perpendicular to each other and to the direction of propagation. The vibrating electric vector E and the direction of wave propagation form a plane.

6.3 Polarized Light

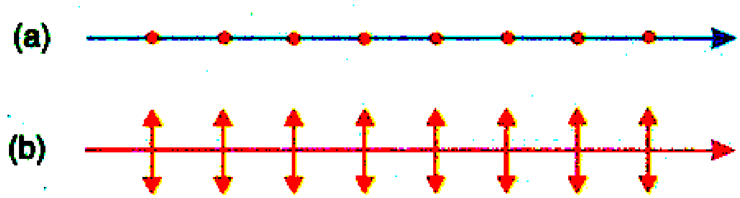
The simplest type of an electromagnetic wave is a wave in which the direction of vibrations of electric vector **E** is strictly confined to a single direction in the plane perpendicular to the direction of propagation of the wave. Such a light is said to be ***plane polarized light***.



Cartesian description of plane polarised light.

A plane-polarized light wave is a wave in which the electric vector is everywhere confined to a single plane.

A linearly polarized light wave is a wave in which the electric vector oscillates in a given constant orientation.



6.4 PRODUCTION OF LINEARLY POLARIZED LIGHT

Linearly polarized light may be produced from unpolarized light using of the following five optical phenomena:

(1) Reflection

(2) Refraction

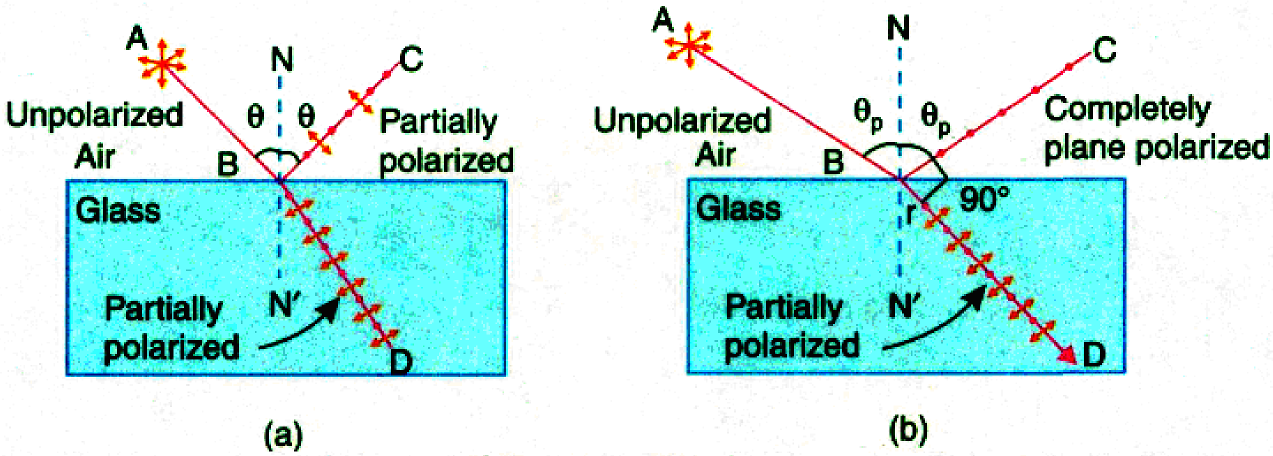
(3) Scattering

(4) Selective absorption

(5) Double Refraction

6.4.1 Polarization by Reflection

E.L. Malus, the French engineer discovered in 1808 polarization of natural light by reflection from the surface of glass. He noticed that when natural light is incident on a plane sheet of glass at a certain angle, the reflected beam is plane polarized.



Production of plane polarized light by the method of reflection–(*a*) When an unpolarized light is incident on a reflecting surface, the reflected and refracted beams are partially polarized. (*b*) The reflected beam is completely polarized when the angle of incidence equals the polarizing angle θ_p, which satisfies Brester's law.

6.4.1.1. Brewster's Law

Sir David Brewster performed a series of experiments on the polarization of light by reflection at a number of surfaces. He found that the polarizing angle depends upon the refractive index of the medium. In 1892, Brewster proved that **the tangent of the angle at which polarization is obtained by reflection is numerically equal to the refractive index of the medium.**

If θ_p is the angle and μ is the refractive index of the medium, then

$$\mu = \tan \theta_p$$

This is known as Brewster's law.

Brewster found that the maximum polarization of reflected ray occurs when it is at right angles to the refracted ray. It means that $\theta_p + r = 90°$.

$$\therefore \quad r = 90° - \theta_p$$

According to Snell's law,

$$\frac{\sin \theta_p}{\sin r} = \frac{\mu_2}{\mu_1}$$

$$\frac{\sin \theta_p}{\sin (90° - \theta_p)} = \frac{\mu_2}{\mu_1}$$

or

$$\frac{\sin \theta_p}{\cos \theta_p} = \frac{\mu_2}{\mu_1}$$

$$\therefore \quad \tan \theta_p = \frac{\mu_2}{\mu_1}$$

The last equation shows that the polarizing angle depends on the refractive index of the reflecting surface. The polarizing angle θ_p is also known as **Brewster angle** and denoted as θ_B. **Light reflected from any angle other than Brewster angle is partially polarized.**

Application of Brewster's law:

(i) Brewster's law can be used to determine the refractive indices of opaque materials

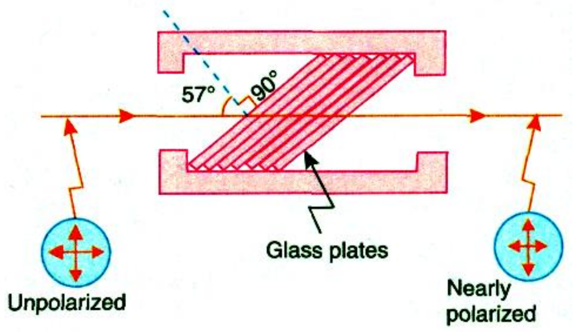
(ii) It helps us in calculating the polarizing angle if the refractive index is known.

(iii) Two windows known as **Brewster windows** are used in gas lasers. They are arranged at Brewster angle at the two ends of the laser tube.

(iv) Another application utilizes the Brewster angle for transmitting a light beam into or out of an optical fiber without reflection losses.

6.4.2 Polarization by Refraction - Pile of Plates

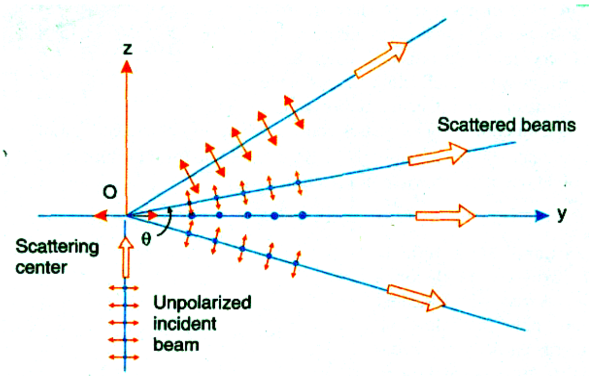
When unpolarized light is incident at Brewster angle on a smooth glass surface, the reflected light is totally polarized while the refracted light is partially polarized. If natural light is transmitted through a single plate, the transmitted beam is only partially polarized. If a stack of glass plates is used instead of a single plate, reflections from successive surfaces occurs leading to the filtering of the s-component in the transmitted ray. Ultimately, the transmitted ray consists of p-component alone. Such an arrangement is called a **pile of plates**.



However, this method of polarizing light is also not efficient because a good portion of light is lost in reflections.

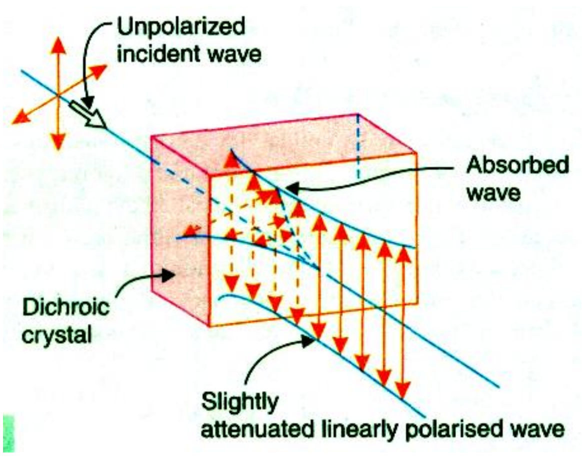
6.4.2 Polarization by Scattering

If a narrow beam of natural light is incident on a transparent medium containing a suspension of ultramicroscopic particles, the light scattered is partially polarized. The degree of polarization depends on the angle of scattering. The beam scattered at 90° with respect to the incident direction is linearly polarized. Sunlight scattered by air molecules is polarized. The maximum effect is observed on a clear day when the Sun is near the horizon. The light reaching an observer on the ground from directly overhead is polarized to the extent of 70% to 80%.



6.4.3 Polarization by Selective Absorption

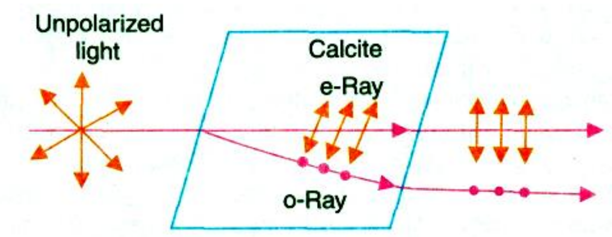
In 1815 Biot discovered that certain mineral crystals absorb light selectively. When natural light passes through a crystal such as tourmaline, it is split into two components, which are polarized in mutually perpendicular planes. The crystal strongly absorbs light that is polarized in a direction parallel to a particular



plane in the crystal but freely transmits the light component polarized in a perpendicular direction. This difference in the absorption for the rays is known as **selective absorption or dichroism.** Crystals that exhibit selective absorption are ***anisotropic.*** The difficulty of this method is that the crystals cannot be grown to sufficiently bigger size.

6.4.4 Polarization by Double Refraction

The double refraction phenomenon was discovered in 1669 by Erasmus Bartholinus during his studies on calcite ($CaCO_3$) crystals, which are known more as Iceland spar. When light is incident on a calcite crystal, it is split into two refracted rays differing in their properties. The phenomenon of causing two refracted rays by a crystal is called **birefringence or double refraction.** The crystals are said to be **birefringent.**



The two rays produced in double refraction are linearly polarized in mutually perpendicular directions. One of the rays obeys Snell's law of refraction and hence is known as an **ordinary ray or o-ray.** The other ray does not obey Snell's law and is called an **extraordinary ray or e-ray.** Hence, the two rays can be distinguished from each other. If one of the rays is eliminated, the light transmitted by the crystal will be a linearly polarized light.

Comparison between o-ray and e-ray

1- Ordinary ray obeys the conventional laws of refraction, whereas the e-ray does not conform to them.

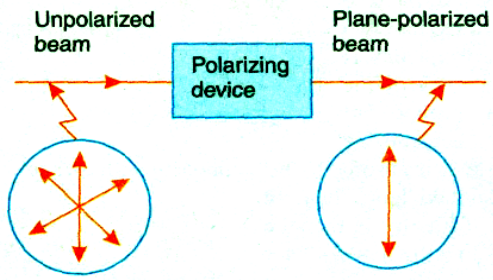
2- Both o-ray and e-ray are plane polarized. The electric vector of o-ray vibrates perpendicular to the principal section of o-ray while the vibrations of e-ray take place parallel to the principal section of e-ray.

3- o-ray travels with the same speed in all directions within the crystal. The e-ray travels with different speeds along different directions in the crystal.

4- Because o-ray travels with the same velocity in all directions, the refractive index corresponding to it has a constant value. On the other hand, the refractive index for e-ray varies from direction to direction.

6.5 Polarizer and Analyser

A polarizer is an optical device that transforms unpolarized light into polarized light. If it produces linearly polarized light, it is called a **linear polarizer.** A linear polarizer is associated with a specific direction called the **transmission axis** of the polarizer. If natural light is incident on a linear polarizer, only that vibration that is ***parallel*** to the transmission axis is allowed through the polarizer while the vibration that is in a ***perpendicular*** direction is totally blocked.



A polarizer transforms unpolarized light into polarized light.

An analyzer is a device, which is used to identify the direction of vibration of linearly polarized light. A polarizer and an analyzer are fabricated in the same way and have the same effect on the incident light.

6.6 Effect of Polarizer on Natural Light

When unpolarized light passes through a polarizer, the intensity of the transmitted light will be exactly half that of the incident light. We can prove this as follows. Let E_o be the amplitude of vibration of one of the waves of the unpolarized light incident on the polarizer. Let E_o make an angle θ with the transmission axis of the polarizer. E_o may be resolved into its rectangular components E_x and E_y. The polarizer blocks the component E_x and transmits the component E. The intensity of the transmitted light is then:

$I = E_y^2 (\cos\theta)^2 = E_o^2 \cos^2\theta = I_o \cos^2\theta$

In unpolarized light, all values of θ starting from 0 to 2π are equally probable.

$$\therefore \quad I = I_0 \langle \cos^2\theta \rangle$$

$$= \frac{I_0}{2\pi}\int_0^{2\pi} \cos^2\theta \, d\theta$$

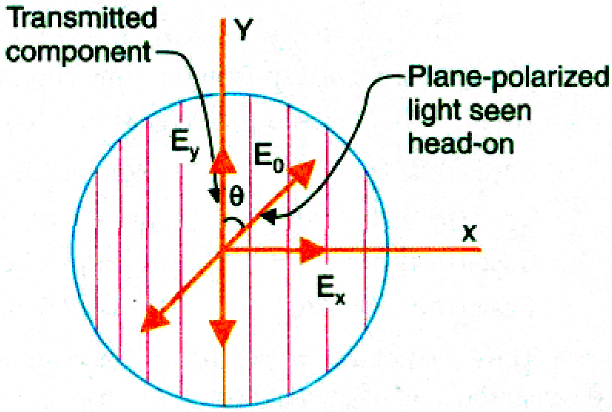
$$= \frac{I_0}{2\pi}\int_0^{2\pi} \left(\frac{1+\cos 2\theta}{2}\right) d\theta$$

$$= \frac{I_0}{4\pi}\left[(\theta)_0^{2\pi} + \left\{\frac{\sin 2\theta}{2}\right\}_0^{2\pi}\right]$$

$$= \frac{I_0}{4\pi}(2\pi + 0)$$

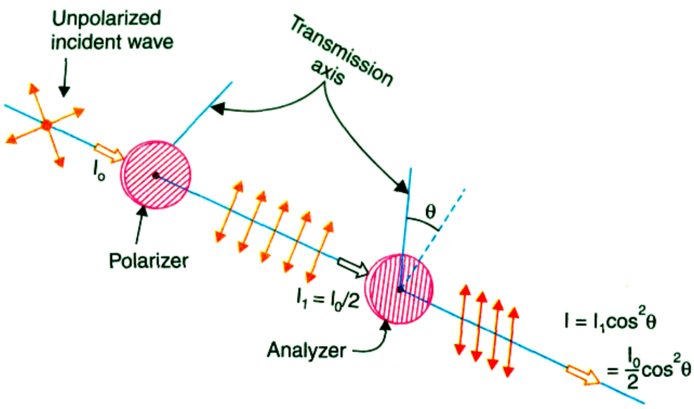
$$\therefore \quad I = \frac{1}{2} I_0$$

Thus, **if unpolarized light of intensity I_0 is incident on a polarizer, the intensity of light transmitted through the polarizer is $I_0 / 2$.**



Action of a polarizing sheet on a linearly polarized wave oriented at an angle θ w.r.t. the transmission axis. The component E_x is absorbed and E_y component is transmitted.

6.7 Effect of Analyser on Plane Polarized Light (Malus' Law)



When natural (unpolarized) light is incident on a polarizer, the transmitted light is linearly polarized. If this light further passes through an analyzer, the intensity varies with the angle between the transmissions axes of the polarizer and analyzer. Malus studied the phenomenon in 1809 and formulated the law that bears his name. It states that the ***intensity of the polarized light transmitted through the analyzer is proportional to cosine square of the angle between the plane of transmission of the analyzer and the plane of transmission of the polarizer. This is known as Malus' law.***

$$E_y = E \cos\theta$$

The intensity corresponding to this component is

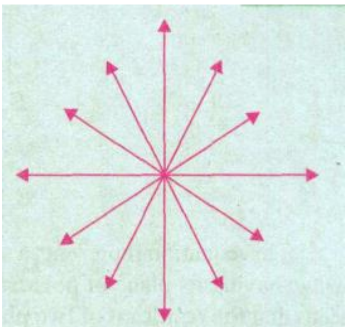
$$I = E^2 \cos^2\theta = I_1 \cos^2\theta = (I_o/2) \cos^2\theta$$

Case (i): If $\theta = 0°$	axes parallel	$I = I_1$
Case (ii): If $\theta = 90°$	axes perpendicular	$I = 0$
Case (i): If $\theta = 180°$	axes parallel	$I = I_1$
Case (i): If $\theta = 270°$	axes perpendicular	$I = 0$

Thus, we obtain two positions of maximum intensity and two positions of zero intensity when we rotate the axis of the analyser with respect to that of the polarizer.

6.8 Types of Polarized Light

We can now sum up the various types of polarized light as follows.



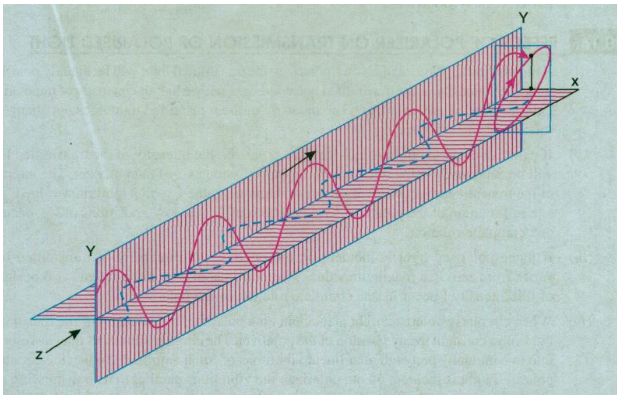
Schematic representation of partially polarized light.

(1) Unpolarized light, which consists of sequence of wave trains, all oriented at random. It is considered as the resultant of two optical vector components, which are incoherent.

(2) Linearly polarized light, which can be regarded as a resultant of two coherent linearly polarized waves.

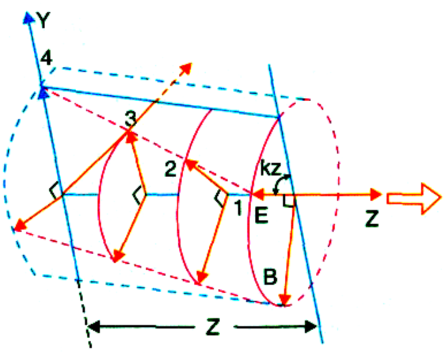
(3) Partially polarized light, which is a mixture of linearly polarized light and unpolarized light.

(4) Elliptically polarized light, which is the resultant of two coherent waves having different amplitudes and a constant phase difference of 90°. In elliptically polarized light, the magnitude of electric vector E changes with time and the vector E rotates about the direction of propagation.



Elliptically polarised light is produced when two orthogonal coherent waves having different amplitudes and a phase difference of 90°, superpose on each other.

(5) Circularly polarized light, which is the resultant of two coherent waves having same amplitudes and a constant phase difference of 90°. A light wave is said to



be ***circularly polarized,*** if the magnitude of the electric vector E stays constant but the vector rotates about the direction of propagation such that it goes on sweeping a circular helix in space.

6.9 Effect of Polarizer on Transmission of Polarized Light

(1) If unpolarized light is incident on a polarizer, the transmitted light will be linearly polarized light. The intensity of the transmitted polarized light will be half the intensity of unpolarized light incident on the polarizer.

(2) If partially polarized light is incident on a polarizer, the intensity of the transmitted light will be dependent on the direction of the transmission axis of the polarizer. The intensity of the transmitted light will vary from a maximum value I_{max} to a minimum value I_{min} in one full rotation of the polarizer. Two positions of I_{max} and two positions of I_{min} occur in one complete rotation.

(3) If plane polarized light is incident on the polarizer, the intensity of transmitted light varies from zero to a maximum value. Two positions of zero intensity and two positions of full intensity occur in one complete rotation of the polarizer.

(4) When circularly polarized light is incident on a polarizer, the intensity of the transmitted light stays constant in any position of the polarizer. When the circularly polarized light is incident on the polarizer, the vibrations parallel to its transmission axis pass through the polarizer while the perpendicular component is obstructed. When the polarizer is rotated, there is always a component of constant intensity parallel to the axis of the polarizer, which is freely transmitted. Hence, the intensity of the transmitted light is the same for all positions of the polarizer.

(5) In case of elliptically polarized light, the intensity of the light transmitted through the polarizer varies with the rotation of the polarizer from I_{max} to I_{min}. I_{max} is found when the polarizer axis coincides with the semi-major axis of the ellipse and I_{min} occurs when the polarizer axis coincides with the semi-minor axis of the ellipse.