## 3.1 LIGHT

The light has transverse nature (*i.e.* vibrations are perpendicular to its propagation). Like other electromagnetic radiation, light is regarded as an oscillating electric field coupled with an oscillating magnetic field at right angles to each other and perpendicular to the direction of propagation (Figure 1). As electric field vector $\boldsymbol{E}$ is quite large than magnetic field vector $\boldsymbol{B}$, therefore vibration of electric vector is taken as the vibration of light.

**Plane of Vibration:** The plane containing electric vector $\boldsymbol{E}$ and the direction of propagation of the wave is called the plane of vibration (POV).
**Plane of Polarization:** The plane perpendicular to plane of vibration in which no vibrations occur is known as plane of polarization (POP). As shown in Figure 2.

## 3.2 UNPOLARIZED LIGHT

Light from any source is generally ***unpolarized light*** (UPL), *i.e.* it consists of vibrations in any plane perpendicular to the direction of propagation. At one point and time the vibrations is in just one direction and is not the same for other points at that time. It also changes rapidly and randomly at each point with time. Hence it is pictorially presented by a star, as shown in Figure 3a. Any vibration of unpolarized light can be resolved into two perpendicular components, one in a direction parallel to *transmission axis* and other in a direction perpendicular to it, as shown in Figure 3b.

## 3.3 POLARIZED LIGHT

When a beam of unpolarized light passes through any uniaxial crystal (such as tourmaline, calcite or quartz), then it is found that the electric vector of emergent beam of light oscillates only in one particular direction. Then such an emergent light beam is said to be ***linear*** or ***plane polarized light***, in short LPL or PPL (see Figure 4).

The direction of electric vibration of emergent beam will depend on the transmission axis of crystal. When the plane of vibration of polarized light is in the plane of the paper, they are represented by *vertical arrows* (Figure 5a), while that perpendicular to the plane of the paper are presented by *dots* (Figure 5b).

Thus, ***polarization of light*** is the phenomenon in which the vibrations of any ordinary light along a particular direction get absorbed or eliminated by any material (such as Polaroid or uniaxial crystal) or method (such as by reflection or refraction or scattering) and the component perpendicular to it passes through it. In other words, *polarization is a process in which vibrations of light restricts itself only in one plane, i.e. in plane of vibration*.

## 3.4 PRODUCTION AND ANALYSIS OF POLARIZED LIGHT

The common methods for the production and analysis of plane polarized light (PPL) may be grouped under the following heads;

(a) **Polarization by Selective Absorption: POLAROID**
Polaroid is made of tiny crystals of *quinine idosulphate* all lined up in the same direction in a sheet of *nitrocellulose*. Crystals such as these which transmit light vibrations in one

particular plane and selectively absorbed those vibrate in a mutually perpendicular plane (Figure 6), are said to be *dichoric*. The property of selective absorption is known as ***dichorism***. Thus, *if an unpolarized light beam passed through a Polaroid, the emergent beam will be linearly polarized*.

### (b) Polarization by Reflection: BREWSTER'S LAW

In 1808, **Malus** discovered that when unpolarized light falls on glass (or any other transparent medium) at one particular incidence angle, called ***polarizing angle*** $i_p$, the component with vibration parallel to the plane of incidence is entirely reflected, while perpendicular vibration component is partially refracted and partially reflected (see the Figure 7). Thus, the refracted beam is *partially polarized*, but the reflected beam is *completely polarized*, as it contains vibrations perpendicular to the plane of incidence, only.

**Brewster** discovered that, at polarizing angle the reflected and refracted beams are at right angles to each other. Thus, from Figure 7 we have, $i_p + 90° + r_p = 180°$ and therefore the angle of refraction $r_p$ is equal to, $90° - i_p$. From Snell's law we have

$$n = \frac{\sin i_p}{\sin r_p} = \frac{\sin i_p}{\sin\left(90° - i_p\right)} = \frac{\sin i_p}{\cos r_p}$$

or, $\quad n = \tan i_p$

or, $\quad i_p = \tan^{-1}(n)$

The tangent of the angle of polarization is equal to the refractive index of the reflecting medium; this is called **Brewster's law**. Therefore, polarizing angle is also known as ***Brewster's angle***. For air-glass interface, it is equal to 57°.

### (c) Polarization by Uniaxial Crystal: DOUBLE REFRACTION

If a beam of unpolarized light falls on a uniaxial crystal at crystal to one of its faces. Then the single beam will split into beam at the crystal surface (Figure 8). The double bending of a beam transmitted through calcite is called ***double refraction***.

If the two emerging beams are analyzed with a Polaroid, they are found to be plane polarized but their planes of vibrations would be at right angles to each other. One of the ray (known as *ordinary ray* or ***o-ray***) will follow the Snell's law of refraction, but other (known as *extraordinary ray* or ***e-ray***) will not obey the Snell's law.

The speed of the *o-ray* is the same in all the direction, whereas the speed of *e-ray* is different in different directions, because the calcite is an *anisotropic* medium. Along a particular direction the speed of *e-ray* and *o-ray* are equal. This direction is known as the *optic axis* of the crystal, therefore these crystals (such as calcite, quartz or tourmaline) are known as ***uniaxial crystal***.

For *o-ray* the uniaxial crystal has a single index of refraction $n_o$, but for *e-ray* the index of refraction varies with direction from $n_o$ to $n_e$. The quantities $n_o$ and $n_e$ are called the *principle indices* of refraction for the uniaxial crystal.

**Huygens's Explanation of Double Refraction:** The behavior for the speed of the two rays, *o-ray* and *e-ray* spreading in calcite is summarized in Figure 9, which shows two wave surfaces spreading out from an imaginary point source S embedded in the crystal.

1. The particular direction in which $v_o = v_e$ is called *optic axis*. The *o-ray* surface is a *sphere*, because the medium is isotropic for the *o-ray*. The *e-ray* surface is an *ellipsoid of revolution* (EOR) about the optic axis.
2. The *o-ray* and *e-ray* both are linearly polarized. The vibrations of the *o-ray* are always at right angles to the optic axis, as well as to the direction of its propagation. For the *e-ray*, the direction of vibrations lies in the plane containing the optic axis and at right angles to the propagation of ray.
3. If the ellipsoid of revolution lies completely outside the sphere, *i.e.* if the speed of the *e-ray* is greater than *o-ray* in all direction (Figure 10a), then the crystal is known as a ***negative crystal***. For example; calcite, KDP, ADP, etc.
4. If the ellipsoid of revolution lies completely inside the sphere, *i.e.* if the speed of the *e-ray* is less than *o-ray* in all direction (Figure 10b), then the crystal is known as a ***positive crystal***. For example; quartz, ice, wurzite, etc.

Thus, according to **Huygens's theory of wavelets**, *every point of the doubly refracting crystal, disturbed by the incident wave is to be considered as the source of two secondary wavelets – sphere for the ordinary ray and ellipsoid of revolution (about the optic axis) for the extraordinary ray*.

### (d) Polarization by Nicol Prism:

Nicol prism is an optical device made from a crystal of calcite and used for producing and analyzing plane polarized light.

**Principle: William Nicol** utilized the phenomenon of *total internal reflection* at a thin film of *Canada balsam* separating the two pieces of calcite to eliminate the ordinary ray from the unpolarized light to obtain plane polarized light.

**Construction:** To construct a Nicol prism, calcite *rhombohedra* of length three times of its width is used. The end NR and N'R' are cut artificially to form new faces PR and P'R', respectively, so as to reduce the angles to a more acute angle of 68° instead of 71°. The crystal is then cut along the shorter diagonal PP'. The cut surface are polished and cemented together with a thin layer of *Canada balsam* which is transparent and whose refractive index $n_{cb}$ lies between the refractive indices of calcite for the *o-ray* ($n_o$) and *e-ray* ($n_e$), *i.e.* $n_o > n_{cb} > n_e$. For sodium light of wavelength 5893Å, $n_o$ = 1.65836, $n_{cb}$ = 1.55 and $n_e$ = 1.48641. The end faces PR and P'R' of the Nicol prism are left clear while the others (P'R and PR') are painted black, as shown in Figure 11.

**Action:** A ray AB of monochromatic unpolarized light entering the prism through the face PR, almost parallel to P'R (or PR'), splits into *o-ray* and *e-ray* whose vibrations are perpendicular and parallel to the principal section of the Nicol prism, respectively. The *o-ray* incident at C enters into a rarer medium (Canada balsam) from a denser medium (calcite for *o-ray*). It is therefore totally internally reflected for angle of incidence on the Canada balsam greater than the critical angle,

$$\theta_c = \sin^{-1}\left(\frac{n_{cb}}{n_o}\right) = \sin^{-1}\left(\frac{1.550}{1.658}\right) = 69°$$

The *e-ray* is passing from a rarer (calcite for *e-ray*) into a denser medium (Canada balsam) and therefore it is transmitted through the balsam, suffering a slight deviation in path. Finally the plane polarized *e-ray* emerges from the Nicol prism parallel to the incident ray.