5

Polarization

5.01. INTRODUCTION

The phenomena of interference and diffraction confirm the wave nature of light. However, neither of these phenomenon is able to identify the nature of waves that light is. That is, these phenomena do not tell as whether the light waves are longitudinal or transverse. Also, we cannot know about the nature of oscillations connected with light—linear, circular, elliptical etc—from the study of interference and diffraction. This is accomplished from the study of another phenomenon called polarization and that is the subject of this chapter.

The electromagnetic nature of light specifically requires, that the light consists of transverse waves and that the oscillations are confined to the plane of the wave front. From the study of polarization we will find that only such w ves can be polarised.

5.02. ELECTROMAGNETIC NATURE OF LIGHT AND ITS DESCRIPTION

Like all other em waves, the light waves also consist of electric and magnetic vectors which oscillate in phase with each other in the free space. The direction of the oscillation of these vectors is perpendicular to each other as well as to the direction of propagation of the em waves As before, for describing the em character of light, we assume that the light is propagating in the X-direction and the electric and magnetic vectors are oscillating along the Y and Z directions respectively. That is :

$$\vec{E} = \hat{j}\, E_y \text{ and } E_y = E_0 \cos(\omega t - kx)$$

Also $$\vec{H} = \hat{K} H_z \text{ and } H_z = H_0 \cos(\omega t - kx)$$

The em character and the various phenomena connected with the light may be described either in terms of electric or magnetic vector. However, we prefer the description with the help of electric vector because as explained in the chapter on em waves, the maximum value of the electric vector is much larger in magnitude than that of the magnetic vector. Also, it has been established through experimental studies by Drude, Nerst and Weiner that the electric vector affects the eye or the photographic plates more and it is this vector that determines the intensity of the observed light.

10^{-8} second

5.03 POLARIZATION OF LIGHT

The light waves are emitted when the electrons of the excited atoms jump from some higher orbit to some lower orbit. This process of jumping down occurs in about 10^{-8} second. Each time it occurs, an em pulse or wave train of about 10^{-8} s duration goes out. That is, the length of the wave is limited to the space, that can be traversed by light in about 10^{-8} second. Each of these wave trains oscillates in a certain mode with the electric and magnetic vectors oscillating in certain constant orientation perpendicular to each other and also perpendicular to the direction of propagation of the wave. The orientation of the electric and magnetic vectors, in general, may vary from wave train to wave train and thus the light from the given source is a sequence of randomly oriented electric or magnetic vectors.

Unpolarized light. *The light, in which the wave trains have electric (or magnetic vectors oscillating in randomly distributed directions is said to be* **unpolarized.** It may be denoted as shown in fig. 5.03.1 (*a*).

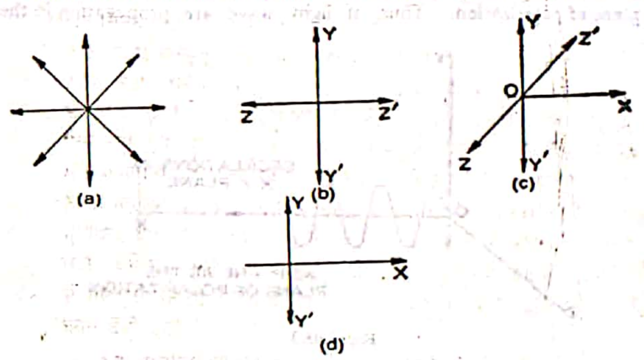

Fig. 5.03.1

The different electric vectors may be resolved along the Y and Z directions and the unpolarized light may be represented as shown in fig. 5.03.1 (*b*). Here, the direction of propagation of the wave is perpendicular to the plane of the paper. Conventionally, it may also be depicted as shown in fig. 5.03.1 (*c*). However, to have a much simplified pictorial representation, we prefer to denote the unpolarised light as shown 5.03.1 (*d*). Here, the dot on the inter section of the perpendicular lines represents the oscillations perpendicular to the plane of the paper.

Plane polarized light. *If the electric vectors of all the wavetrains in a beam of light oscillate in a certain constant orientation, the light is said to be linearly polarized.* It is so called because the projection of the wave on a plane perpendicular to the direction of propagation is a line. See fig. 5.03.2 (*a*) and (*b*). For the oscillations in the plane of the paper it may be depicted as shown in fig. 5.03.2 (*c*) and for oscillations perpendicular to the plane of the paper it may be depicted as shown in fig. 5.03.2 (*d*).

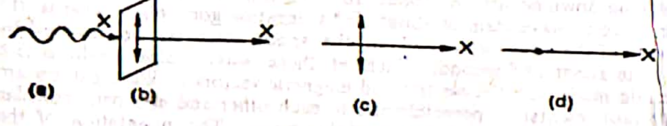

Fig. 5.03.2

The linearly polarized light is also called *plane polarized*. This takes the three dimensional representation into account. Because the oscillations and propagation of such a light is in a plane.

The plane in which oscillations take place is called **plane of oscillations.** And the plane perpendicular to the plane of oscillations is called **the plane of polarization.** Thus, if light wave are propagating in the

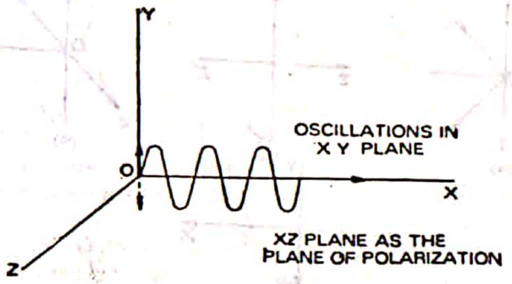

Fig. 5.03.3

X-directions and the electric vector is oscillating in the *Y* direction, then *XY* plane is the plane of oscillations and the *X—Z* plane is the plane of polarization. See fig. 5.03.3. The component of the electric vector in the plane of polarization is zero.

Circularly polarized light. In the circularly polarized light, the

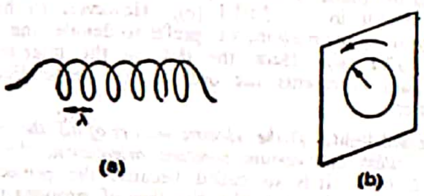

Fig. 5.03.4

direction of oscillation of the electric (also magnetic) vector rotates periodically, but the magnitude remains constant. The location of the head of the electric vector always lies on a helix. The electric vector completes one rotation in one length of the wave. See fig. 5.03.4.

Elliptical polarized light. In the elliptically polarized light also the direction of oscillation of the electric vector rotates periodically, but *magnitude varies* within certain maximum and minimum limits. The location of the head of the electric vector always lies on a flattered helix. The rotation of the vector, in this case also is completed in one length of the wave. See fig. 5.03.5.

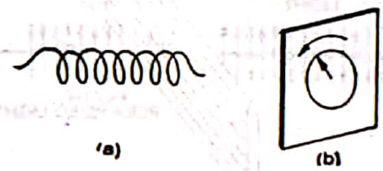

Fig. 5 03.5

The elliptically polarized light lies between the circularly and linearly polarized lights as shown in fig. 5.03.6.

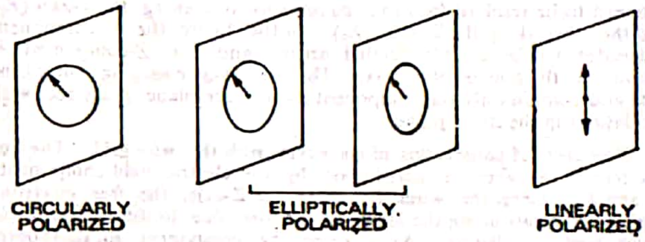

Fig. 5.03.6

Partially polarized light. The mixture of polarized and unpolarized light is called partially polarized light.

Polarization of light. The process of obtaining polarized light from unpolarized or partially polarized light is called polarization of light. In the following sections we will discuss various methods of polarizing the light.

5.04. WIRE GRID POLARIZER

A device used to produce polarised light out of the unpolarised light is called polarizer. One such device is called **wire grid polarizer. Construction.** In 1888, Heinrich Hertz used grids as polarizers to test the properties of radio waves he had discovered in the year 1887. It consists of an array of thin wires arranged parallel to one another as shown in fig. 5.04.1. The wires are made of material like copper, which is a good conductor of electricity. Suppose a beam of unpolarized em waves is incident on the wire grid lying in the YZ plane, as shown in fig. 5.04.1. The incident em waves are propagating along the

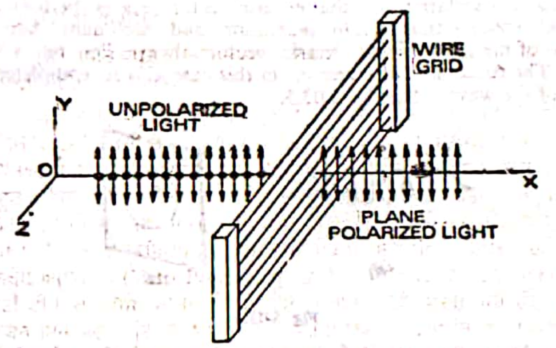

Fig. 5.04.1

X-axis. The electric field vectors of the unpolarised light may be assumed to be resolved into two componets one along the Y-axis (E_y) and the other along the Z-axis (E_z). In the figure the Y component is denoted by the double headed arrows and the Z-component is denoted by the dots on the X-axis. The em waves emerging out of the wire grid contain only the component E_y and are plane polarized, with oscillations in the X—Y plane.

The cause of polarization of em waves with the wire grid. The free electrons in the wires are acted upon by the electric field components E_y and E_z. Since, the wires lie along the Z-axis, the free electrons begin to oscillate along the length of the wire due to the action of E_z, which itself is oscillating. As a result the component E_z, disappears because of the following two reasons.

(*i*) The oscillating electrons act as dipoles source of electromagnetic waves in all directions except the direction of oscillation of the electrons. It is found that the phase of the electric vector of the em waves so emitted by the oscillating electron is 180° out of phase with the electric vector E_z, that causes the oscillations of the electrons. The superposition of the two, therefore, leads to the cancellation of each others effect. So, no electric vector along the Z-axis, propagates beyond the wire grid.

(*ii*) A part of the energy is dissipated due to the collision of the electrons with the lattice imperfections. Also, the motion of electrons along the length of the wire constitutes a current, which dissipates energy as heat and this results in the attenuation of the component E_z. However, the main reason for the disappearance of E_z is the superposition of incident waves and those emitted due to the oscillation of the electrons in the wires.

The component E_y also acts on the free electrons in the metallic wire. Due to E_y, the free electrons are set into oscillations along the transverse directions. But the wires being very thin, the electrons cannot oscillate freely, nor their amplitude can be large. As a result negligible amount of em waves are emitted. Also, the path along which the electrons may move is so short, that negligible energy is dissipated due to lattice imperfections or Joules heating etc. Because of these reasons, the component E_y is not attenuated and it propagates beyond the wire grid. Thus, the em waves propagating beyond the wire grid are plane polarised.

Difficulties in fabricating wire grid polarizer for light waves. For complete attenuation of one of the rectangular components of the electric vector, the interwire spacing in the wire grid should be much less than the wavelength of the em waves. So, it is easy to design a wire grid polarizer for micro waves ($\lambda \simeq 1$ cm) which was successfully demonstrated by Hertz. However, for the optical region, that is for the visible region of the em spectrum λ is of the order of 550 nm $= 5{\cdot}5 \times 10^{-5}$ cm. It is not easy to obtain a wire grid having inter wire separation of the order of 10^{-5} cm or less. In 1933, G.R. Bird and M. Parrish made attempts in this direction by depositing gold atoms in the ridges of a transparent grating. The steam of gold atoms was incident at grazing angle on the diffraction grating in an evacuated chamber. The ridges of the grating got coated with gold atoms and formed very very thin wires. Thus they could obtain a wire grid polarizer which could be used for polarizing light. However, this technique is not very suitable for commercial use. In the next section, we will explain some more techniques for obtaining polarizers for light on the principle of wire grid.

Transmission and absorption axes. Fig. 5.04.2 shows two lines YY' and ZZ' drawn through the wire grid polarizer. After transmission

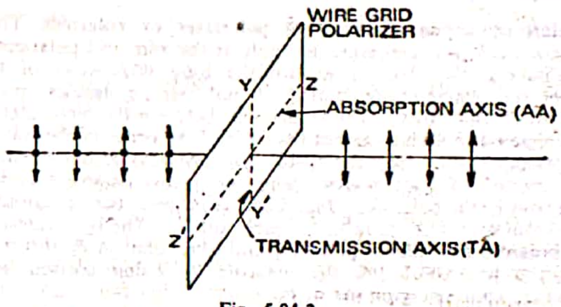

Fig. 5.04.2.

through the wire grid, oscillations of the electric vector parallel to ZZ'

are cut off or absorbed completely and that parallel to YY' are completely transmitted. Therefore, YY' is termed as transmission axis (TA) and ZZ' is termed as absorption axis (AA). These terms will be used in the next sections to discuss the transmission and absorption of em waves.

5.05. SHEET POLARIZERS OR POLAROIDS

William Bird Herapath (1820—1868) in 1852 had observed that quinine idosulphate (now commonly know as herapathite) possesses the property of selective absorption of light waves in the same way as the wire grid polarizer does for micro-waves. But the size of these crystals is so small that they cannot be used for large scale polarisation of light. In 1932, *E.H.* Land of United States invented the technique for alligning the herapathite crystals as long chains parallel to each other. This sets their transmission axis (TA) and absorption axis (AA) respectively to each other. These crystal chains are packed together in thin sheet of parallel nitro cellulose and we obtain the polarizer for light in the form of thin sheets. They are called **sheet polarizers** or **polaroids**.

H-sheets or polaroids. Recently sheet polarizers or polaroids have been obtained by heating and stretching the polyvinyl alcohol films so that complex molecules are lined up (in the direction of streching) as long chains. These molecules are then impregnated with iodine to increase their electric conductivity. The iodine atoms provide conduction electrons. The separation between the iodine atoms is of the order of 31 nm. The polaroid sheets prepared in this way are called *H*-sheets or *H*-polaroids. These were devised by *E.H.* Land in 1938.

K-polaroids. Land and Rogers discovered that when stretched (oriented) polyvinyl alcohol film is heated in the presence of an active dehydrating catalyst such as HCl, film darkens slightly and become strongly dichoric. It is called **K-polaroid**. It is not bleached by sunlight and is very useful, for example, as acutomobile head lights. The polaroid films are generally mounted between thin optically plane glass sheets.

Polarizing action of the sheet polarizers or polaroids. The sheet polarizers work on the same principle as the wire grid polarizer or the tourmaline crystals Here, instead of the long thin wires of the grid polorizer; we, employ long chains of polymer molecules possessing high electric conductivity. The separation between the molecular chains can be reduced to such as extent that it is of the order of the wavelength of the visible light. So, the visible light can also be polarized. Only electric vector of light waves along the transmission or optical axis emerges out of the polaroid. Fig. 5.05.1 (a) shows two polaroides with their transmission axis parallel to each other. The light emerging out of the polaroid P_1 is plane polarized and the polaroid P_2 also transmits it. In the fig. 5.05.1 (b), the polaroid P_2 being crossed with P_1, absorbs the light emerging out of P_1.

In the ideal case, we expect a transmission of 50% of the light incident on the polaroid. However, in actual pratice the

transmission may be of the order of 35%. The decrease in the amount of transmission is due to the reflection on the two surfaces of the polaroid.

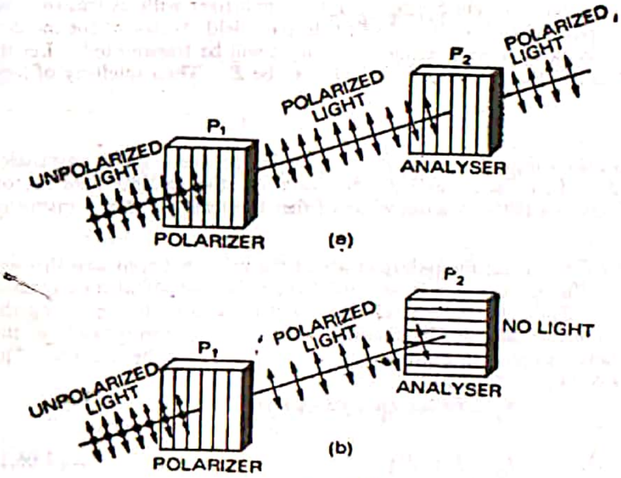

Fig. 5.05.1.

sheet and absorption of light by the material of the polaroid due to reasons other than the absorption of electric vector due to the wire grid action.

Uses of polaroids. 1. Polaroid may be fitted in the head lights of automobiles as well as their wind screen to avoid glare. The transmission axes of the polaroids both in the head lights as well as the wind screen are oriented say at 45° with the vertical. This minimizes the glare and the drivers are not dazzled by the lights of the vehicle approaching from the opposite side.

2. Polaroid sheets can be used as window screens. For this purpose two polaroid sheets are mounted one behind the the other. By rotating one of the polaroid sheet, the amount of light entering the room can be controlled. This is often done in blg hotles and aeroplanes, because of the high costs involved.

3. Polaroids can be used in sun glasses to avoid glare. The light reflected from the horizontal surfaces has more horizontal oscillations of the electric than the vertical component. By using polaroids, the horizontal component can be further attenuated and glare can be reduced considerably.

5.06. MALUS LAW

Suppose a beam of polarized light is propagating along X-axis and is having XY as the plane of oscillations. The electric field vector of

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the lightwaves in such a case should be parallel to Y-axis. Since, the wire grid polarizer transmits the electric field vector perpendicular to the length of the wires, we call that direction as **transmission direction** of the polarizer. To start with we put the polarizer with its transmission direction parallel to Y-axis. As the electric field vector of the incident light is also along Y-axis, whole of the light will be transmitted. Let the magnitude of the electric field vector be E. Then intensity of light will be :

$$I_0 = E^2$$

Here the suffix '$_0$' indicates the angle between the transmission direction of the polarizer and the direction of the electric field vector. It also indicates the maximum value of the intensity of the transmitted light.

Now if we rotate the polarizer about the light beam as axis through an angle θ the transmission direction of the polarizer will also be rotated through θ. The component of the electric field vector 'E' along the transmission direction will be $E \cos \theta$. Therefore, the magnitude of the electric field vector transmitted by the polarizer will be $E \cos \theta$. The intensity of the transmitted light will be :

$$I_\theta = [E \cos \theta]^2 = E^2 \cos^2 \theta$$

or $$I_\theta = I_0 \cos^2 \theta \qquad \ldots(5\ 06.1)$$

This is called Malus Law equation and it gives the intensity of the polarized light transmitted by a polarizer in a particular orientation.

Malus Law may be stated as follows : *The intensity of the plane polarized light transmitted by a polarizer, having the transmission direction inclined at an angle θ with the direction of the electric field vector, is 'cos' θ' time the maximum intensity of the light transmitted by the polarizer.*

5.07. PROBLEM

Unpolarised light falls on two polarising sheets placed one on top of the other. What must be the angle between the transmission directions of the sheets if the intensity of the transmitted light is $\frac{1}{3}$rd of the maximum intensity of the transmittad beam ? Consider that the sheet is ideal *i e.* it reduces the intensity of unpolarised light by exactly 50%.

Solution.

Let I_m = intensity of the unpolarised light

The intensity I of the polarised beam transmitted by the first sheet would be

$$I_0 = \tfrac{1}{2} I_m \qquad \ldots(i)$$

Here I_0 = maximum intensity of transmitted beam

Let θ = angle between the transmission directions of the two sheets

Then according to Malus Law, the intensity of the light transmitted by the second sheet is

$$I_\theta = I_0 \cos^2 \theta$$

But $I_\theta = \frac{1}{3} I_0$

$\therefore$ $\frac{1}{3} I_0 = I_0 \cos^2 \theta$

or $\frac{1}{3} = \cos^2$

or $\cos \theta = \pm \frac{1}{\sqrt{3}}$

$\therefore$ $\theta = \cos^{-1}\left(\pm \frac{1}{\sqrt{3}}\right)$

$= \pm 54{\cdot}7°$

5.08. RELATION BETWEEN REFRACTIVE INDEX AND CHARACTERISTIC IMPEDANCE

If 'v' be the velocity of light in the dielectric medium and c be the velocity of light in free space, then refractive index n is given by :

$$n = \frac{c}{v} \qquad \ldots(\mathrm{I})$$

Now $c = \dfrac{1}{\sqrt{\mu_0 \epsilon_0}}$, $v = \dfrac{1}{\sqrt{\mu \epsilon}}$ and

$$\vec{Z} = \sqrt{\frac{\mu}{\epsilon}} \text{ and } \vec{Z_0} = \sqrt{\frac{\mu_0}{\epsilon_0}}$$

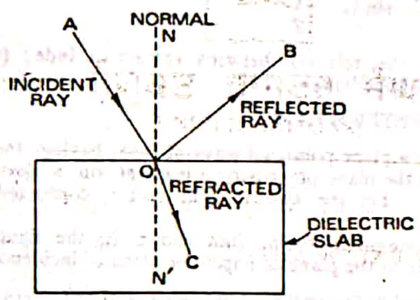

Fig. 5.08,1

where $\vec{Z}$ and $\vec{Z_0}$ are the characteristic impedances, μ and μ_0 are the permeabilities and ϵ and ϵ_0 are the permittivities of the dielectric medium and free space respectively.