Polarisation

- The interpretation of the phenomena of interference and diffraction on the basis of wave theory conclude that light is a wave motion.
- When a periodic disturbance travels through a material medium, particles in its path are set into vibration- leading to wave
- Two types of vibration- longitudinal, transverse
- Particles of the medium vibrating along the path of the wave propagation- longitudinal
- Particles of the medium vibrating in any path which is perpendicular to the path of the wave propagation – transverse
- On the basis of interference and diffraction phenomena, it is impossible to comment on the nature of vibration of electric field E associated with light wave – they are independent of it
- Maxwell's electromagnetic theory of light, light wave is transverse electromagnetic wave
- Polarization of light provides the information about the vibration of the E fields associated with the light wave.
- In longitudinal Wave the vibrations of the medium are parallel to the direction of propagation. If we draw several planes through the direction of propagation, vibrations will look exactly similar- longitudinal wave is symmetrical in nature

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- Transverse wave, there are infinite direction of vibrations are possible for the particles which are perpendicular to the direction of wave propagation - if we look towards the vibrations of the particles of the medium from different angles about the direction of propagation, it will be quite different – transverse wave is asymmetrical in nature
- If a restriction is imposed on the different possible directions of the vibrations of the particles perpendicular to the path of a wave propagation, so that their vibrations are confined only to a single plane, i. e. only along one direction which is perpendicular to the direction of wave propagation – outgoing wave is called polarized wave
- Sunlight and almost every other form of natural and artificial illumination produces light waves whose electric field vectors vibrate in all planes that are perpendicular with respect to the direction of propagation
- The ultimate agent for registering the information is either the eye or photographic film, which registers the average effect as a result, such symmetrical nature of a transverse wave can be noticed only if we observe a limited portion of the wave or observe it momentarily

Light wave

- A plane electromagnetic wave consists of vibrating electric field vector and magnetic field vector being mutually perpendicular to each other.
- Both of them are perpendicular to the direction of propagation of the wave
- That is why light wave is called transverse electromagnetic wave
- The electric vector is only responsible for optical effects and hence called as the light vector
- By suitable devices the electric vector may be constrained to describe the same locus – linear, circular or elliptical of fixed orientation transverse to the direction of propagation of wave
- Accordingly we shall say linearly, circularly or elliptical polarized wave

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- When the vibration of the particles of the medium perpendicular to the path of the transverse wave propagation occurs in all possible directions with equal favour, then the wave is called unpolarised.
- Common light sources like sunlight and other produce unpolarized light
- Human eye lacks the ability to distinguish between randomly oriented and polarized light, plane polarized light can only be detected through an intensity or color effect

CHAPTER 3
POLARISATION OF LIGHT

Polarisation: *Polarisation, Qualitative discussion on Plane, Circularly and Elliptically polarized light, Malus law, Brewster's law, Double refraction (birefringence) - Ordinary and Extra-ordinary rays, optic axis etc.; Polaroid, Nicol prism, Retardation plates and analysis of polarized lights.* ***[4]***

1. Introduction:

1. The successful interpretation of the phenomena of interference and diffraction of light on the basis of wave theory established conclusively that like sound, light is a wave motion. However, on the basis of these phenomena it is not possible to comment on the nature of vibration of the **E** fields associated with the light wave, because the phenomena of interference and diffraction are independent on it. Another group of experiments, which are related, with another property of light called the *polarization of light* provide the information about the vibration of the **E** fields associated with the light wave. This phenomenon demands for its explanation that light must be a *transverse wave motion.*

2. Polarization of a wave:

3 In a longitudinal wave the vibrations of the medium are parallel to the direction of propagation. As a result, if we draw several planes through the direction of propagation, vibrations will look exactly similar, i.e. longitudinal wave is perfectly symmetrical in nature. On the other hand, a transverse wave is asymmetrical in nature. If we look towards the vibrations of the particles of the medium from different angles about the direction of propagation, it will be quite different. This want of symmetry of every transverse wave is called as the *polarization* of the wave. The ultimate agent for registering the information is either the eye or photographic film, which registers the average effect as a result, such asymmetrical nature of a transverse wave can be noticed only if we observe a limited portion of the wave or observe it momentarily.

4 According to electromagnetic theory of light, a light wave consists of vibrating electric and magnetic fields being mutually perpendicular to each other; both being perpendicular to the direction of propagation of the wave. The electric vector is only responsible for the optical effects and hence called as the light vector. By suitable devices the electric vector may be constrained to describe the same locus-linear, circular or elliptical of fixed orientation transverse to the direction of propagation of the wave. Accordingly we shall have linearly, circularly or elliptically polarized wave.

2.1. Linear Polarization:

We can represent the two orthogonal optical disturbances in the following form

$$\mathbf{E}_x(z,t) = \mathbf{i}\, E_{ox} \cos(kz-wt) \qquad (1)$$

and

$$\mathbf{E}_y(z,t) = \mathbf{j}\, E_{oy} \cos(kz-wt+\varepsilon). \qquad (2)$$

Where ε is the relative phase difference between the waves, both of which are traveling along the z-direction. The resultant optical disturbance will be the vector sum of these two perpendicular waves:

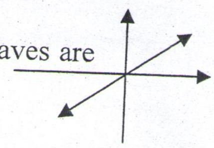
$$\mathbf{E}(z,t) = \mathbf{E}_x(z,t) + \mathbf{E}_y(z,t) \qquad (3)$$

If ε is zero or an integral multiple of $\pm 2\pi$, the waves are said to be in phase. In that case Eq. (3) becomes

$$\mathbf{E} = (\mathbf{i}E_{ox} + \mathbf{j}E_{oy}) \cos(kz\text{-}wt) \qquad (4)$$

The resultant wave thus has fixed amplitude equal to $(\mathbf{i}E_{ox} + \mathbf{j}E_{oy})$; in other words, it too is *linearly polarized.* There one sees a single resultant **E** oscillation, along a tilted line, continuously in time. On the reverse, *we can resolve a plane polarized light into two orthogonal components.*

Suppose now that ε is an odd integer multiple of $\pm\pi$. The two waves are said to be 180° out of phase, and



$$\mathbf{E} = (\mathbf{i}E_{ox} - \mathbf{j}E_{oy}) \cos(kz\text{-}wt) \qquad (5)$$

This wave is again linearly polarized, but the plane of vibration has been rotated from that of the previous condition.

2.2. Circular Polarization:

Plane polarized light represents the simple type of polarization. For such light the light vector vibrates simple harmonically along a fixed line perpendicular to the direction of propagation. When two plane polarized beams of monochromatic light are superimposed, then under suitable conditions the resultant light vector may rotate in a plane perpendicular to the direction of propagation. If the magnitude remains constant while the orientation varies regularly the tip of the light vector traces a circle and the resultant light is said to be circularly polarized.

Let $E_{ox} = E_{oy} = E_o$ and in addition their relative phase-difference $\varepsilon = -\pi/2 + 2m\pi$, where m=0, ±1, ±2,….. Accordingly

$$\mathbf{E}_x(z,t) = \mathbf{i}\, E_o \cos(kz\text{-}wt) \qquad (6)$$

and

$$\mathbf{E}_y(z,t) = \mathbf{j}\, E_o \sin(kz\text{-}wt). \qquad (7)$$

The consequent wave is given by

$$\mathbf{E} = E_o\, [\mathbf{i} \cos(kz\text{-}wt) + \mathbf{j}\, E_o \sin(kz\text{-}wt)] \qquad (8)$$

Now the scalar amplitude of **E** $[(\mathbf{E}.\mathbf{E})^{1/2}]$ is constant but the direction of **E** varies with time and the rotation of the **E** vector is clockwise at an angular frequency w, as seen by an observer toward whom the wave is moving. Such a wave is said to be *right-circularly polarized.* In comparison, if $\varepsilon = \pi/2 + 2m\pi$, then **E** rotates counterclockwise and the wave is referred to as *left-circularly polarized.*

A linearly circularly polarized wave can be synthesized from two oppositely polarized circular waves of equal amplitude. If the amplitudes of the two constituent plane-polarized waves are unequal the resultant wave will be elliptically polarized. *Interested readers may derive it.*

3. Ordinary light and the representation of plane polarized light:

In general, ordinary light beam having vibrations along all possible planes perpendicular to the direction of propagation of light is said to be unpolarized. Ordinary polarized light is represented by star.

As was mentioned before that plane polarized light will have vibration along a single line being perpendicular to the direction of propagation. Two different types of plane polarized lights are shown in the figure below. When the plane polarized light has vibrations in the plane of the paper they are represented by straight arrows as shown in Fig. c. When the vibrations lie in a direction perpendicular to the plane of the paper they are represented by dots as shown in Fig.d.

3.1. Plane of polarization and plane of vibration:

The plane containing the direction of propagation of light but containing no vibrations is called *plane of polarization.*

The plane containing the direction of vibration and direction of propagation of light is called *plane of vibration.*

4. Polarizers:

At this stage we have the idea of what polarized light is. The next step is to develop an understanding of the techniques used to generate it, change it, and in general manipulate it as per our needs. A polarizer is a optical device which polarized the light input into it. For example, recall that one possible representation of unpolarized light is the superposition of two equal-amplitudes, incoherent orthogonally polarized states. An instrument that separates these two components, discarding one and passing on the other, is known as a *linear polarizer.* Depending on the form of the output, we could have *circular* or *elliptical polarizers.*

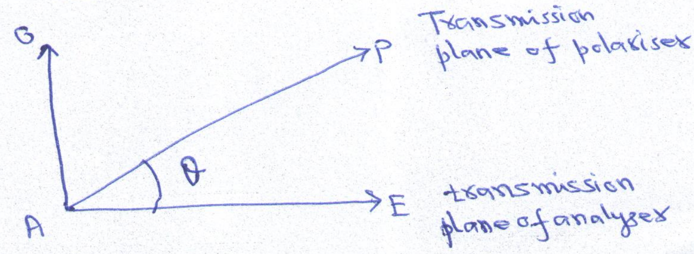
Polarizers are based on the four fundamental physical mechanisms: *dichroism*, or selective absorption; *reflection*; *scattering*; and *birefringence*, or double refraction. There is, however, one underlying property that they all share, which is simply that there must be some form of asymmetry associated with the process. In truth, the asymmetry may be a subtle one related to the incident or viewing angle, but usually it is an obvious anisotropy in the material of the polarizer itself.

4.1. Law of Malus:

In 1809 Malus discovered experimentally that when a beam of completely plane polarized light is incident on an analyzer, the intensity of the emergent beam varies as the square of cosine of the angle between the planes of transmission of the analyzer and the polarizer. This law is known as the law of Malus. To prove it let the angle between the two planes of transmission of the polarizer and analyzer be θ, and R be the amplitude of the incident plane polarized light wave. The plane polarized light of amplitude R can be resolved into two components along and perpendicular to the plane of transmission of the analyzer as shown in the adjoining figure.

$I = E_0^2 \cos^2\theta = I_0^2 \cos^2\theta$

AE =R cosθ and AO =R sinθ



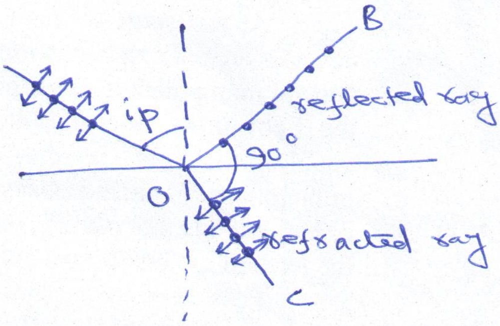
The perpendicular component is eliminated in the analyzer while the parallel component is freely transmitted through it. Therefore, the intensity of light emerging from the analyzer is given by $I_{analyzer} = (R\cos\theta)^2 = I_o \cos^2\theta$, where I_o is the intensity of the completely plane polarized incident light.

4.2. Brewster's law:

In 1881, Sir Brewster, on the basis of his experimental observations, discovered a simple relation between the angle of incidence at which the maximum polarization occurs and the refractive index of the medium. He observed that for a particular angle of incidence called angle of polarization, the reflected light is completely plane polarized with the plane of vibration perpendicular to the plane of incidence. It was shown by him that the tangent of polarizing angle is equal to the refractive index of the medium, that is, $\mu = \tan i_p$.

This is called Brewster's law. Brewster also concluded that at polarizing angle the reflected and refracted rays are right angles to each other. Let a beam AB of an ordinary light be incident on the glass surface at the polarizing angle i_p. A part of it is reflected along ~~BC~~ OB and a part is reflected along ~~BD~~ OC as shown in Figure.

According to Brewster's law



$$\mu = \frac{\sin i_p}{\sin(90^\circ - i_p)} = \tan i_p$$

for glass plate $i_p = 57^\circ$

optic axis of a crystal is a direction in which a ray of transmitted light suffers no birefringence. An optic axis is a direction rather a single line. All rays that are parallel to that direction exhibit the same lack of birefringence.

4.3. Doubly Refracting Crystals:

There are certain crystals, which exhibit the property of splitting an incident ray into two refracted rays. Such crystals are called doubly refracting crystals. They are two types (i) Uniaxial crystals and (ii) Biaxial crystals.

In uniaxial crystals there is only a single direction known as optic axis along which two refracted rays are transmitted with the same velocity. Out of two refracted rays only one follows the ordinary laws of refraction. The examples of these crystals are calcite, tourmaline, quartz, beta-barium borate, Cesium Lithium barium borate, potassium dihydrogen phosphate etc.

In biaxial crystals, there are two directions or two optic axes along which the velocities of refracted rays are same. None of the refracted rays obeys the laws of refraction. Examples of biaxial crystals are copper sulphate, cane sugar, mica, Urea, potassium titanyl phosphate etc.

4.4. Polarization by selective absorption:

Dichroism

Some doubly refracting crystals possess the property of selective absorption. Such crystals not only produce two beams (ordinary and extraordinary) polarized in direction right angles to each other but also absorb one of the polarized components much more strongly than the other. In a crystal of proper thickness, one of the component is completely removed by absorption; whereas the other is transmitted. The crystal exhibiting this property are said to be dichroic and the phenomenon is known as dichroism. The most prominent example of dichroic crystal is tourmaline. For example, if a beam of unpolarised light is incident normally on a thick (about 1 mm) crystal of tourmaline, cut with its faces parallel to the optic axis is split up into ordinary and extraordinary beams; both being plane polarized. The ordinary beam is completely absorbed in the crystal; while extraordinary beam is partly absorbed and emerges from the crystal. In this way plane polarized light with vibrations in the plane of incidence is produced.

Physical explanation of the dichroism of crystalline material:

We can get a qualitative picture of the mechanism that gives rise to crystal dichroism by considering the microscopic structure of the material. The atoms within a crystal are strongly bound together by short-range forces to form a periodic lattice. The electrons, which are responsible for the optical properties, can be envisioned as elastically tied to their respective equilibrium positions. Electrons associated with a given atom are also under the influence of the surrounding nearby atoms, which themselves may not be symmetrically distributed. As a result, the elastic binding forces on the electrons will be different in different directions. Accordingly, their response to the harmonic electric field of an incident electromagnetic wave will vary with the direction of **E**. If in addition to being anisotropic the material is absorbing, a detailed analysis would have to include an orientation-dependent conductivity. Current will exist, and the energy from the wave will be converted into joule heat. The attenuation, in addition to the direction dependence may also depend on the frequency. This means that if the incoming white light is in a P-state, the crystal will appear colored, and the color will depend on the orientation of **E**. The substances that display two or even three different colors are said to be dichroic or trichroic, respectively.

4.5. Polaroid

Polaroid is an artificial crystalline material, which can be made in thin sheets and has the property of producing plane polarized light by the method of selective absorption. It is a large sized plane polarizing film polymer molecules mounted between the two glass plates. This film consists of a thin sheet of nitrocellulose containing ultramicroscopic crystals of herapathite (iodosulphate of quinine) with their optic axes parallel to each other. When a light beam is incident on such a polaroid, the molecules absorb those components which vibrate perpendicular to the polarizing direction and transmit only those components whose light vectors vibrate parallel to this direction. Thus the transmitted light is plane polarized.

Recently other types of polaroids are formed by stretching polyvinyl alcohol films so as to orient the molecules with their longer axes in the direction of stress. When the film is impregnated with iodine, it acts as dichroic. The polaroid film is placed between two glass plates. Such polaroids are called H-polaroids. H-polaroids transmit 33% more light than the herapathite polaroids. When the stretched polyvinyl alcohol film is heated with dehydrating agent, e.g. HCl, it slightly darkens but exhibits strong dichroism. This is called K-polaroids.

4.6. Use of Polaroids:

Polaroid's have wide applications in everyday life.

(i) The polaroids are usually very effective in producing and analysing Polarized light.

(ii) The most common use of Polaroids is to avoid the glare of light. The light reflected from bright surfaces, such as wet roads, cover glasses of paintings, polished tables, and is partly plane polarized having more horizontal vibrations than vertical. The horizontal vibrations are avoided by using Polaroid sunglasses. We see the objects in diffused light.

(iii) Another interesting application of Polaroid is the elimination of dazzling light of a car approaching from opposite direction. The cover glasses of headlights and windscreen are covered with Polaroid discs so that the vibration plane of the transmitted light is at 45° to the horizontal. The driver can see to the light of his own headlight while that from on coming vehicle is cut-off. However, road and other objects are visible by light scattered by them. For this purpose K-polaroids are used.

(iv) The Polaroids are also used to control the amount of light entering in aeroplanes from outside. One Polaroid is fixed outside the window while the other is rotation-able and is fitted inside. By rotating the rotatable Polaroid disc the intensity of light inside the plane can be controlled.

(v) Polaroids are frequently used for viewing 3-D movies.

(vi) Polaroids are also used to improve the colour contrast in old oil painting.

(vii) Polaroids are used in studying optical properties of metals and in analysing the crystals.

(viii) Fitting Polaroids in front of the camera-lens can take distinct photographs of clouds.