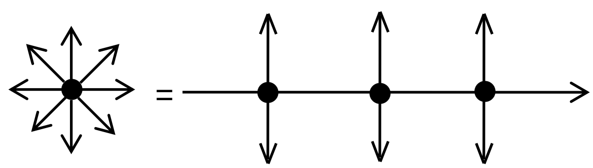
Polarization

Introduction:

The experiments on interference and diffraction have established that light is a form of wave motion. But what type of wave motion it is - transverse or longitudinal? Maxwell's electromagnetic theory predicts light to be a transverse wave. The studies on polarization of light waves experimentally established this transverse wave nature of light. Longitudinal waves like sound waves do not exhibit polarization. The natural light is unpolarized which can be transformed into different types of polarization using simple optical devices. The unaided human eye can not distinguish between unpolarized light and polarized light.

A thorough understanding of the concept of polarization is highly essential in the wave propagation through wave guides and optical fibres. Polarization has many useful engineering applications, one of them being in liquid crystal displays which are widely used in wrist watches, calculators and video displays etc.

Q 1) What is Unpolarized light? (Short Answer question).



Unpolarized light

Light which has the same property in all directions or a light wave symmetrical about a direction is called unpolarized light. Unpolarized light is a light wave, in which Electric field vector oscillates in more than one plane. Examples are light emitted by the Sun, an incandescent lamp or flame.

Ordinary light consists of independent wave trains whose planes of vibrations are randomly oriented about the direction of propagation. The electric field vectors vibrate in all directions perpendicular to the ray. The light is transverse but there is no preference for any particular direction. The random orientation of the planes of vibrating electric vectors leads to equal probability of all directions and to their symmetrical distribution about the propagation direction. Hence, the transverse nature of the waves gets concealed. In the above figure, unpolarized light is viewed as two plane polarized waves with a random phase difference.

Q 2) What is Polarized light? (Short Answer question).

Light which has acquired the property of one-sideness or a light wave unsymmetrical about a direction is called polarized light. A polarized light wave is a light wave with a definite direction of oscillation of the electric field vector, which occurs in a single plane or in some specific way. Light with vertical vibration that travels within a single plane is called linearly polarized light while circularly polarized light and elliptically polarized light are the other types of linearly polarized light in which the vibration plane rotates forward.

Polarized light is not produced naturally. It is obtained by converting natural light into polarized light using optical elements.

Q 3) Distinguish between Unpolarized light and Polarized light? (Short Answer question).

	Unpolarized light	Polarized light
1	Consists of waves with planes of vibration equally distributed in all directions about the ray direction.	Consists of waves having their electric vector vibrating in a single plane normal to ray direction.
2	Symmetrical about the ray direction.	Asymmetrical about the ray direction.
3	Produced by conventional light sources.	Is to be obtained from unpolarized light with the help of polarizers.
4	May be regarded as the resultant of two incoherent waves of equal intensity but polarized in mutually perpendicular planes.	May be regarded as the resultant of two mutually perpendicular coherent waves having zero phase difference.

Q 4) What are the various types of polarization? (Short Answer question).

The polarization of a light wave describes the shape and locus of the tip of the electric field vector ***E*** in the plane perpendicular to the direction of propagation at a given point in space as a function of time. Depending upon the locus of the tip of the ***E*** vector, light may exhibit three different states of polarization. They are

1) Linear polarization (Plane polarization),

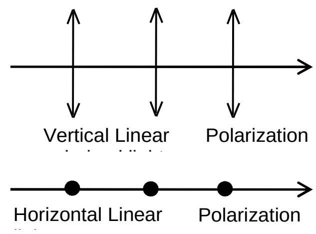
2) Circular polarization,

3) Elliptical polarization.

Apart from these, the light may also be partially polarized. An unaided human eye cannot identify the state of polarization of light.

Q 5) What is linear polarized light? (Short Answer question).

A light wave is said to be linearly polarized, if in the course of wave propagation, the direction of electric field vector ***E*** does not vary with time, but its magnitude varies sinusoidally with time. If the field is pointing either up or down, one can call it as vertical polarization, and if it is pointing either right or left, one can call it as horizontal polarization.

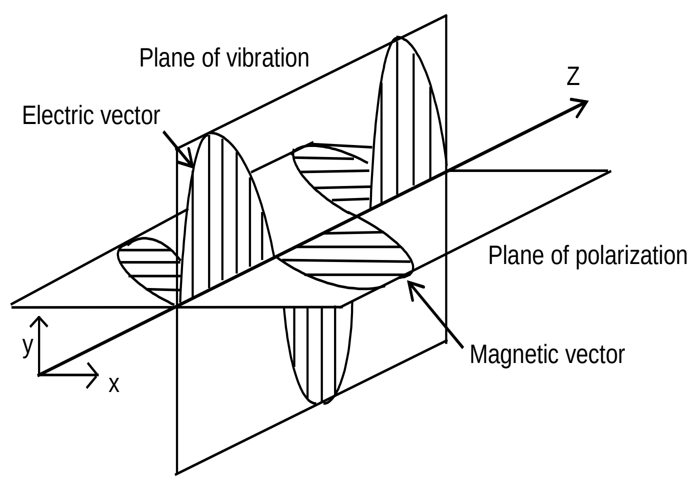


Electric fields are not restricted to pointing exactly along vertical or horizontal axes, but can be at any arbitrary angle to those axes. Linearly polarized light, polarized at any arbitrary angle, may be regarded as a combination of horizontally and vertically polarized light, with appropriate amplitude, and which are oscillating in phase or 180^0 out of phase. The key point is that the two component waves are coherent.

The representation of plane polarized light is shown in the above figure. When the electric field vector oscillates horizontally in a direction perpendicular to the plane of the paper, the light wave is represented by dots. When the electric field vector oscillates vertically in the plane of the paper, the light wave is represented by arrows.

Television transmissions are plane polarized and so the receiver antenna is oriented parallel to the electric field vector of the waves for good reception of the TV programme.

Q 6) What is Plane of polarization and plane of vibration? (Short Answer question).



Light waves are electromagnetic waves. An electromagnetic wave is a transverse wave consisting of electric and magnetic fields vibrating perpendicular to each other and to the direction of propagation. However, in most of the optical phenomena the electric field ***E*** in the light wave rather than the magnetic field ***B*** is normally identified with the wave disturbance because the effects of ***B*** on the human eye and on various light detectors are exceedingly small. The vibrating electric vector ***E*** and the direction of wave propagation constitute a plane called the plane of vibration and in a plane polarized wave all such planes are parallel. The magnetic vector ***B*** and the direction of propagation form a plane and is called the plane of polarization.

Q 7) What is circularly polarized light? (Short Answer question).

A light wave is said to be circularly polarized, if in the course of wave propagation, the magnitude of the electric vector ***E*** stays constant but it rotates at a constant rate about the direction of propagation and sweeps a circular helix in space. In circularly polarized light, there is no preference to specified direction of oscillation.

A circularly polarized light wave may be regarded as the resultant wave produced due to superposition of two coherent linearly polarized waves of equal amplitude oscillating in mutually perpendicular planes, and are out of phase by 90^0.

If the rotation of the tip of ***E*** is clockwise as seen by an observer looking back towards the source, then the wave is said to be right-circularly polarized. If the tip of ***E*** rotates anti-clockwise, then the wave is said to be left-circularly polarized.

Q 8) What is elliptically polarized light? (Short Answer question).

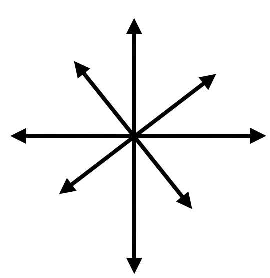
A light wave is said to be elliptically polarized, if the magnitude of electric vector ***E*** changes with time and the vector ***E*** rotates about the direction of propagation and sweeps a flattened helix in space. If we imagine that we are looking at the light wave advancing towards us, we would observe that the tip of the ***E*** vector traces an ellipse in space.

An elliptically polarized light wave may be regarded as the resultant wave produced due to superposition of two coherent linearly polarized waves of different amplitudes, oscillating in mutually perpendicular planes and are out of phase. If waves of different amplitude are related in phase by 90^0, then the resultant light wave is elliptically polarized.

When we are looking back towards the source, if the rotation of E vector occurs clockwise, it is said to be a right-elliptically polarized wave. If it rotates anti-clockwise, it is said to be a left-elliptically polarized wave.

Q 9) What is partially polarized light? (Short Answer question).

Usually, light is neither totally polarized nor unpolarized but a mixture of the two types. It can be viewed as a mixture of plane polarized light and unpolarized light. Partially polarized light is represented in the following figure.



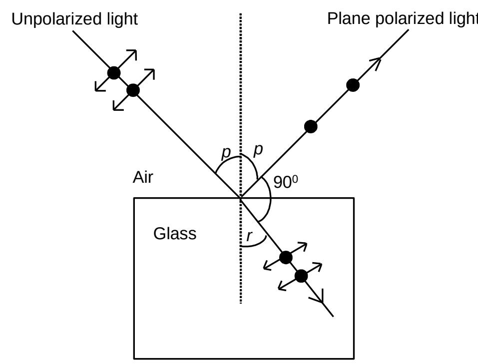
It can be represented in the form of a superposition of two incoherent plane polarized waves having different amplitudes and polarized in mutually orthogonal planes.

Q 10) What are the different methods for production of plane polarized light? (Short Answer question).

Plane polarized light may be produced from unpolarized light using the following five optical phenomena.

(1) Reflection, (2) Refraction, (3) Scattering, (4) Selective absorption, and (5) Double refraction.

Q 11) Describe the production of plane polarized light by reflection or state and prove Brewester's law. (Short Answer question).



The simplest way of producing a plane polarized light is by reflection. When ordinary light is reflected from the surface of a transparent medium like glass, it becomes partially polarized. The degree of polarization varies with the angle of incidence. At a certain angle of incidence called the polarizing angle (angle of polarization), the reflected light is completely polarized.

Brewster proved that the tangent of the angle of polarization (*p*) is numerically equal to the refractive index of the medium.

$\mu = Tan\ p$ **(Brewster's law)**

A direct deduction from this law is that when light is incident at the polarizing angle the reflected and transmitted rays are at right angle to each other.

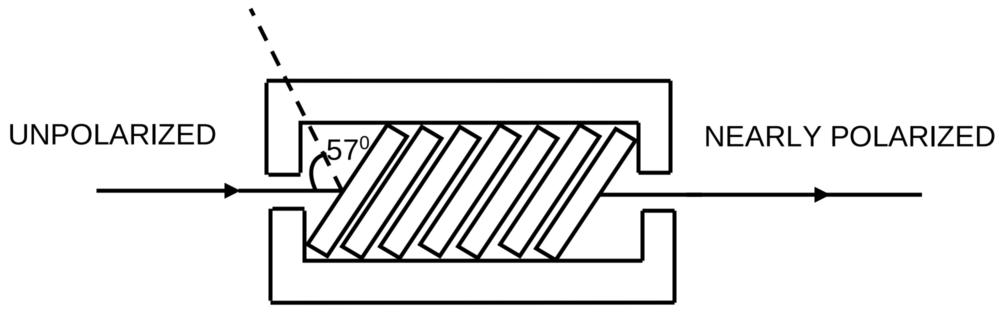
To prove the above statement, consider the above figure.

From Bewester's law,

$\mu = Tan\ p = \dfrac{Sin\ p}{Cos\ p}$ ......(1). From Snell's law, $\mu = \dfrac{Sin\ p}{Sin\ r}$ ......(2)

From *(1)* and *(2),* we get, $Sin\ r = Cos\ p = Sin\ (90^0 - p) \Rightarrow r = 90 - p$ or $r + p = 90^0$

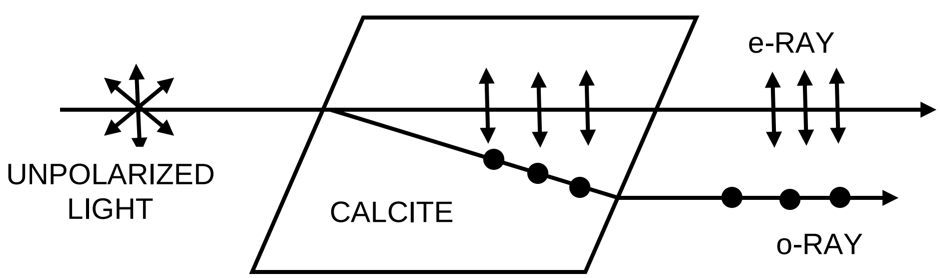
Q 12) Describe the production of plane polarized light by refraction. (Short Answer question).



When unpolarized light is incident at Brewester angle on a smooth glass surface, the reflected light totally polarized, while the refracted light is 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 (perpendicular components represented by dots) in the transmitted ray. Ultimately, the transmitted ray consists of p-component (parallel components represented by arrows) alone.

It is found that a stack of about 15 glass plates is required for this purpose. The glass plates are supported in a tube of suitable size and inclined at an angle of about 33^0 to the axis of the tube. Such an arrangement is called a pile of plates. Unpolarized light enters the tube and is incident on the plates at Brewester angle and the transmitted light will be totally polarized parallel to the plane of incidence.

Q 13) Describe the production of plane polarized light by Double refraction. (Short Answer question).

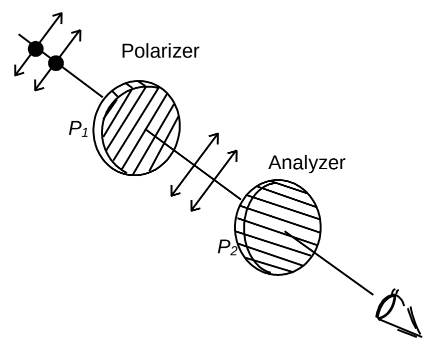


When a beam of unpolarized light is allowed to fall on a calcite crystal or quartz crystal, it is split up into two refracted beams in place of the usual one as in glass. The phenomenon is called double refraction or birefringence and such crystals are called doubly-refracting crystals.

The two refracted rays are plane polarized. The refracted ray which obeys the laws of refraction and having vibrations perpendicular to the principal section of the calcite crystal is known as the ordinary ray or the 0 - ray. The other refracted ray which does not obey the laws of refraction and having vibrations in the principal section is called the extraordinary ray or the e-ray. A single linearly polarized ray is obtained in practice through elimination of one of the two polarized rays.

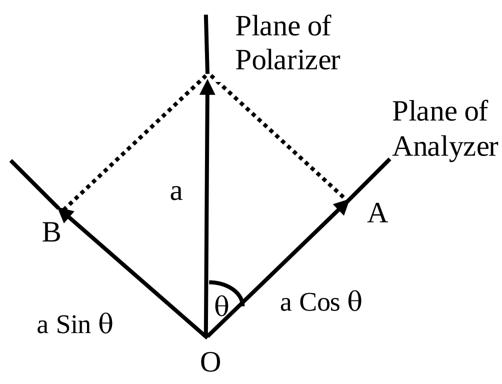
Q 14) State and explain the law of Malus.

The figure shows two polarizing sheets P_1 and P_2. There exists in each of these sheets a certain characteristic polarizing direction, shown by parallel lines. When unpolarized light falls on P_1, it will transmit only those wave train components whose electric vectors vibrate parallel to this direction and will absorb those that vibrate at right angles to this direction. The emergent light will be plane polarized, the intensity of which can be analyzed by rotating P_2 (called analyzer) using the law of Malus.



According to the law of Malus, the intensity of the light transmitted by the analyzer is proportional to the square of the cosine of the angle between the planes of transmission of analyzer and polarizer.

Let the angle between the plane of polarizer and the analyzer at any instant be θ. Assume OP = a represents the amplitude of vibrations of emergent plane polarized light from the polarizer. This amplitude resolved into two components OA = a Cos θ along the plane of analyzer and OB = a Sin θ is perpendicular to the plane of analyzer as shown.



The parallel component a Cos θ is transmitted by the analyzer while the perpendicular component a Sin θ is reflected. Thus, the intensity of the transmitted light through the analyzer is

$I = (a \cos\theta)^2 = a^2 \cos^2\theta$

$I = I_0 \cos^2\theta$, where $I_0 = a^2$ is the intensity the plane polarized light incident on the analyzer.

Q 15) Write a short note on Double refraction.

When a beam of unpolarized light is allowed to fall on a calcite crystal or quartz crystal, it is split up into two refracted beams in place of the usual one as in glass. The phenomenon is called double refraction or birefringence and such crystals are called doubly-refracting crystals.

The two refracted rays are plane polarized. The refracted ray which obeys the laws of refraction and having vibrations perpendicular to the principal section of the calcite crystal is known as the ordinary ray or the 0 - ray. The other refracted ray which does not obey the laws of refraction and having vibrations in the principal section is called the extraordinary ray or the e-ray.

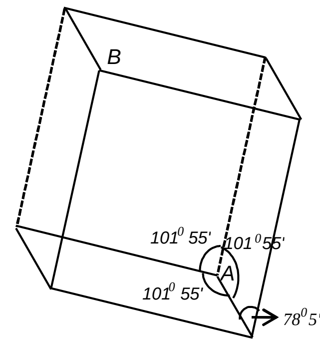
The ordinary ray has the same velocity in all directions and hence its wave front is spherical. In other words, the crystal has, for this ray, a single refractive index μ_0 just like in isotropic solid. Extraordinary ray has different velocities in different directions and hence its wave front is ellipsoid. In other words, the refractive index μ_e for this ray, defined as $\frac{c}{v}$, varies with direction. The quantities μ_0 and μ_e are called the principal indices of refraction for the crystal.

In certain crystals called negative crystals (calcite, tourmaline), the ellipsoid lies outside the sphere. This shows that in negative crystals, the extraordinary wave front travels faster than ordinary wave front except along the optic axis. For such crystals, $\mu_0 > \mu_e$. In certain crystals called positive crystals (quartz), the sphere lies outside the ellipsoid. This shows that the velocity of ordinary wave front is greater than extraordinary wave front except along the optic axis. For such crystals, $\mu_0 < \mu_e$.

In certain crystals called uniaxial crystals (calcite, tournaline, quartz), there is only one direction (optic axis) along which the two refracted rays travel with the same velocity. In certain crystals called biaxial crystals (topaz, mica), there are two such directions along which the velocities are the same.

Q 16) Describe the geometry of calcite crystal. (Short Answer question).

Calcite crystal belongs to rhombohedral class of hexagonal system. The six faces of the rhombohedrum are parallelograms each having angles of $101^0\ 55'$ and $78^0\ 5'$ as shown in the figure. There are two opposite corners *A* and *B* where all the three angles are obtuse. These corners are known as blunt corners. At the rest of the corners, there is one obtuse angle and two acute angles.



Q 17) What is Optic axis in a doubly refracting crystal. (Short Answer question).

A line passing through anyone of the blunt corners and making equal angles with the three edges which meet at this corner, locate the direction of optic axis of the crystal. Optic axis of a crystal is an important because most of the properties of the crystal depend on this.

Optic axis in a crystal is a direction and not a particular line. Any line parallel to this direction can be treated as an optic axis. If light is incident along the direction of optic axis in doubly refracting crystals, the 0 - ray and the e - ray travel along the same direction with equal velocity, making double refraction indistinguishable.

Q 18) What is Principal section of a doubly refracting crystal such as Calcite. (Short Answer question).

Any plane which contains the optic axis and is perpendicular to two opposite faces is called a principal section. As a crystal has six faces, for every point inside the crystal, there are three principal sections, one for each pair of opposite crystal faces. A principal section cuts the crystal surface in a parallelogram having angles 71^0 and 109^0.

Q 19) Explain the propagation of light waves in doubly-refracting crystals.

Fig. 1 shows unpolarized light falling at normal incidence on a calcite slab cut from a crystal such that the optic axis is normal to the surface. According to Huygen's principle, propagation of wavefronts can be considered. No double refraction or speed difference between ordinary ray and extraordinary ray occurs in this case.

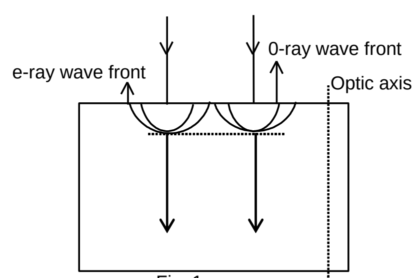


Fig. 1

Fig. 2 shows unpolarized light falling normally on a slab cut so that the optic axis is parallel to its surface. Using Huygen's principle, propagation of wavefronts can be observed. No double refraction occurs because both waves propagate in the same direction without deviation. There is however a speed difference between ordinary and extraordinary rays when they emerge out from the crystal. This case is utilized in the construction of quarter wave plate and half wave plate.

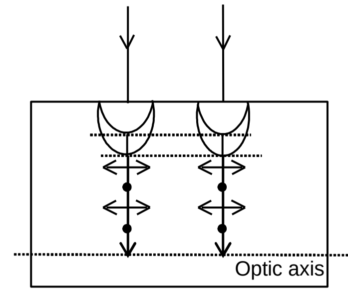
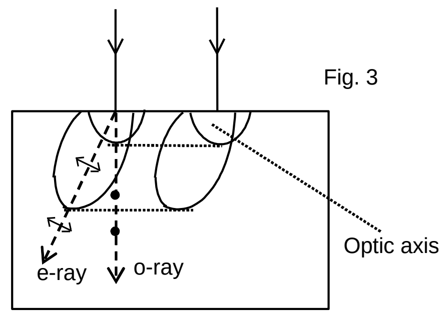


Fig. 2

Fig. 3 shows unpolarized light falling at normal incidence on a calcite slab cut so that its optic axis makes an arbitrary angle with the crystal surface. Both double refraction and a speed difference occurs. By connecting the origin of the wavelet with the point of tangency, one obtains the direction of propagation of the wave.

Fig. 3


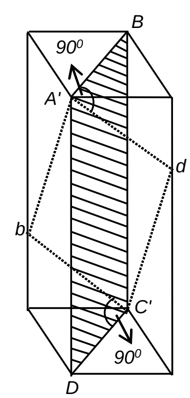
Q 20) Describe the principle, construction and working of Nicol's prism.

Principle:

When light is passed through a doubly refracting crystal, it is split up into ordinary ray and extraordinary ray. Both these rays are plane polarized perpendicular to each other. One of these rays, usually the 0 - ray, is cut off by total internal reflection.

Nicol's prism is an optical device made from calcite crystal and is used in many instruments to produce and analyze plane polarized light.

Construction:

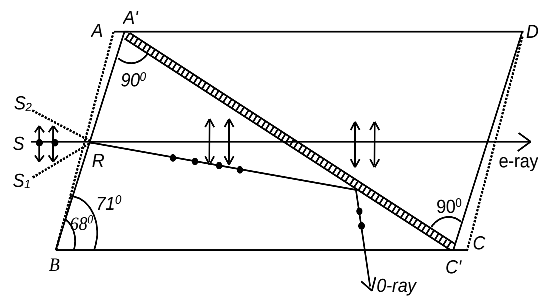


Nicol prism is constructed from a calcite crystal whose length is nearly three times its width. The end faces of the crystal are cut down so as to reduce the angles at *B* and *D* from 71^0 in the principal section to a more acute angle of 68^0 to increase the field of view. The crystal is then cut along the plane *A'bC'd* perpendicular to both principal section *A'BC'D* and the end faces such that *A'd* and *C'b* make an angle of 90^0 with the end faces *A'B* and *C'D*. The two cut surfaces are grounded, polished and made optically flat. Then they are cemented together with Canada balsam which is a transparent glue material.

The refractive index of Canada balsam μ_c has a value which is intermediate between the refractive index of calcite μ_0 for the ordinary ray and μ_e for the extraordinary ray. The sides of the prism are blackened to absorb the totally reflected rays.

Action:

If a ray of light *SR* is incident nearly parallel to *BC'*, it suffers double refraction and gives rise to the extraordinary ray *RE* and the ordinary ray *RO.*



The extraordinary ray passes along *RE* which is plane polarized with vibrations in the plane of the paper. The ordinary ray which is plane polarized normal to the plane of the page suffers total internal reflection at the Canada balsam layer for nearly normal incidence. This is because Canada balsam is optically more dense than calcite for the e - ray and less dense for the 0 - ray. Thus only the e - ray is transmitted. The angle of incidence on the face *AB* is limited to nearly 14^0, otherwise the extraordinary ray will also suffer total internal reflection and no light will emerge out of the prism.

Q 21) What is a Quarter wave plate?

It is a crystal plate of a doubly refracting material of uniaxial crystal cut with its optic axis parallel to the refracting faces. It can produce a phase difference of $\frac{\pi}{2}$ or a path difference of $\frac{\lambda}{4}$ between the ordinary ray and the extraordinary ray when monochromatic plane polarized light of wavelength λ is incident normal to the surface. As light is incident normal to the optic axis, the extraordinary ray and ordinary ray travel in the same direction but with different velocities.

In a calcite crystal which is a negative crystal, the velocity of extraordinary ray is greater than that of ordinary ray, hence $\mu_o > \mu_e$. If t is the thickness of the crystal plate, then the path difference between the two components when they emerge from the plate is $t\ (\mu_o - \mu_e)$. To produce a path difference of $\frac{\lambda}{4}$, we have, $t\ (\mu_o - \mu_e) = \frac{\lambda}{4}$.

$\therefore$ Thickness of the plate $= t = \dfrac{\lambda}{4(\mu_0 - \mu_e)}$. As the thickness depends on wavelength, it is useful only for the wavelength for which it is constructed.

For a quartz crystal which is a positive crystal, $t = \dfrac{\lambda}{4(\mu_e - \mu_0)}$. A quarter wave plate is used for the production and detection of circularly polarized light. In combination with Nicol prism, it is used for analyzing any kind of light. If a plane-polarized light, whose plane of vibration is inclined at an angle of 45^0 to the optic axis, is incident on a quarter wave plate, the emergent light is circularly polarized.

Q 22) What is a Half - Wave plate.

This plate is made from a doubly refracting uniaxial crystal with its refracting faces cut also parallel to the optic axis. The thickness of the plate t is such that it introduces a phase difference of π or a path difference of $\dfrac{\lambda}{2}$ between the ordinary ray and extraordinary ray in passing through it when light is incident normally on the face of the crystal.

For a negative crystal, like calcite, the thickness of the crystal is $t = \dfrac{\lambda}{2(\mu_0 - \mu_e)}$.

For a positive crystal, like quartz, the thickness of the crystal is $t = \dfrac{\lambda}{2(\mu_e - \mu_0)}$.

When plane-polarized light is incident on a half wave plate such that it makes an angle of 45^0 with the optic axis, a path difference of $\dfrac{\lambda}{2}$ is introduced between the e-ray and the 0-ray. The emergent light is then plane-polarized and the direction of polarization of the incident plane polarized light is rotated through 90^0. Thus, a half wave plate rotates the azimuth of a beam of plane-polarized light by 90^0, if the incident light makes an angle of 45^0 with the optic axis of the half wave plate.

Q 23) Describe the production of different polarized light using Nicol's prism, quarter wave plate and half wave plate. (Short Answer question).

Light exhibits three types of polarization apart from the partially polarized and unpolarized states. The three types of polarization are (I) plane polarization (II) circular polarization and (III) elliptical polarization.

Plane-polarized light :

When unpolarized light is incident on a Nicol prism, the emergent light from the Nicol is plane polarized. When Nicol's are used to produce plane polarized light, they are called as polarizers.

Circularly Polarized Light :

Circularly polarized light is the resultant of two light waves of equal amplitudes vibrating at right angles to each other and having a phase difference of $\pi/2$.

Plane polarized light from a Nicol prism is made to fall normally on a quarter wave plate such that its vibration makes an angle of 45^0 with the direction of the optic axis of the quarter wave plate. It is broken into extraordinary ray and ordinary ray of equal amplitudes. On emergence a phase change of $\pi/2$ is introduced between them which results in the formation of a circular vibration and hence outgoing light is circularly polarized.

Elliptically polarized light :

Elliptically polarized light is the resultant of two light waves of unequal amplitudes vibrating at right angles to each other and having a phase difference of $\pi/2$.

Plane polarized light obtained from a Nicol prism is made to fall normally on a quarter wave plate so that the plane of vibration of this light makes an angle other than 45^0 with the direction of the optic axis of the quarter wave plate. It is broken into extraordinary ray with vibrations parallel to the optic axis and ordinary ray with vibrations perpendicular to the optic axis. The amplitudes of extraordinary ray and ordinary ray are different because θ is not equal to 45^0. On emergence through quarter wave plate, a phase difference of $\pi/2$ is introduced between the two rays which combine resulting into elliptic vibration. Hence the outgoing light is elliptically polarized.

SOLVED PROBLEMS

Example 1: A ray of light is incident on the surface of a glass plate ($\mu = 1.55$) at the polarizing angle. Calculate the angle of refraction?

$\mu = Tan\ p = Tan\ i = 1.55$ or $i = Tan^{-1}(1.55) = 57^0\ 11'$. But $i + r = 90^0$. $\therefore\ r = 32^0 49'$

Example 2: Intensity of light through a polarizer and analyzer is maximum when their principal planes are parallel. Through what angle the analyzing Nicol must be rotated so that the intensity gets reduced to 1/4 of the maximum value?

$$I = I_m\,Cos^2\,\theta \Rightarrow \frac{I_m}{4} = I_m\,Cos^2\,\theta \Rightarrow Cos^2\,\theta = \frac{1}{4} \Rightarrow Cos\,\theta = \pm\frac{1}{2} \Rightarrow \theta = 60^0 \text{ or } 120^0$$

Example 3: Calculate the thickness of a half wave plate of quartz for a wavelength of $5000A^0$. Given $\mu_e = 1.553$ and $\mu_0 = 1.544$.

$$t = \frac{\lambda}{2(\mu_e - \mu_0)} = \frac{5000 \times 10^{-8}}{2(1.553 - 1.544)} = 2.78 \times 10^{-3}\ cm$$

Example 4: Plane polarized light passes through a quartz plate with its optic axis parallel to the faces. Calculate the least thickness of the half wave plate for which the emergent beam will be plane polarized. Given $\mu_e = 1.5533$, $\mu_0 = 1.5442$ and $\lambda = 5 \times 10^{-5}\ cm.$

$$t = \frac{\lambda}{2(\mu_e - \mu_0)} = \frac{5000 \times 10^{-5}}{2(1.5533 - 1.5442)} = 2.75 \times 10^{-3}\ cm$$