POLARISATION

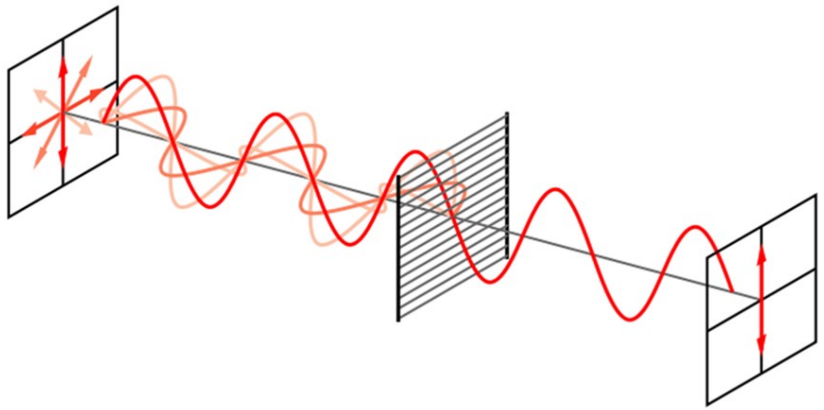
Polarisation

The phenomenon due to which vibrations of light waves are restricted in a particular plane is called polarisation.

In an ordinary beam of light from a source, the vibrations occur normal to the direction of propagation in all possible planes. Such beam of light called unpolarised light.

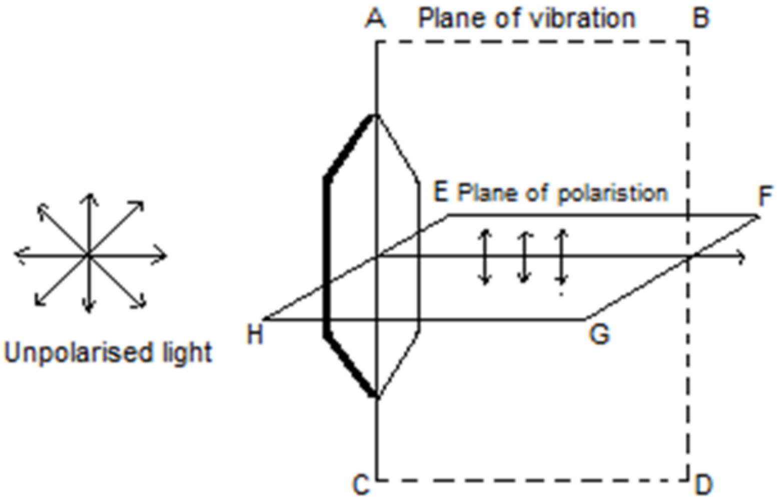
If by some methods (reflection, refraction or scattering) a beam of light is produced in which vibrations are confined to only one plane, then it is called as plane polarised light.

Hence, polarisation is the phenomenon of producing plane polarised light from unpolarised light.



In plane polarised light, the plane containing the direction of vibration and propagation of light is called plane of vibration.

Plane which is perpendicular to the plane of vibration is called plane of polarisation.



In above diagram plane ABCD represents the plane of vibration and EFGH represents the plane of polarisation.

There are three type of polarized light

1) Plane Polarized Light

2) Circularly Polarized Light

3) Elliptically Polarized Light

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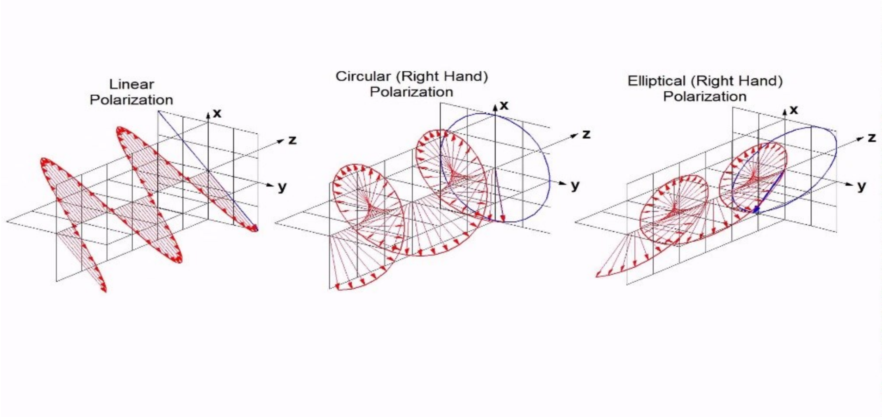
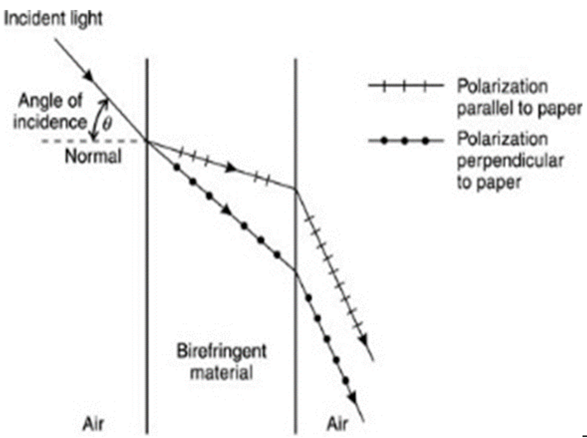


Polarised light can be produced by either reflection, refraction, selective absorption, scattering or by double reflection

Double refraction or birefringence

When ordinary light is allowed to pass through a calcite or quartz , it splits into two refracted beams(O-ray &E –ray) and both are plane polarized lights.



Huygen’s theory of double refraction

According to Huygen’s theory, a point in a doubly refracting or birefringent crystal produces 2 types of wavefronts.

The wavefront corresponding to the O-ray is spherical wavefront. The ordinary wave travels with same velocity in all directions and so the corresponding wavefront is spherical.

The wavefront corresponding to the E-ray is ellipsoidal wavefront. Extraordinary waves have different velocities in different directions, so the corresponding wavefront is elliptical.

Negative crystals

Negative crystals are crystals in which refractive index corresponding to E-Ray (n_E) is less than the refractive index corresponding to O-Ray (n_O) in all directions except for Optic axis.

The E-Ray travels faster than O-Ray except along the Optic axis.

The spherical O-Wavefront is entirely within the ellipsoidal E -Wavefront.

Ex: Calcite , Tourmaline ,Ruby ...

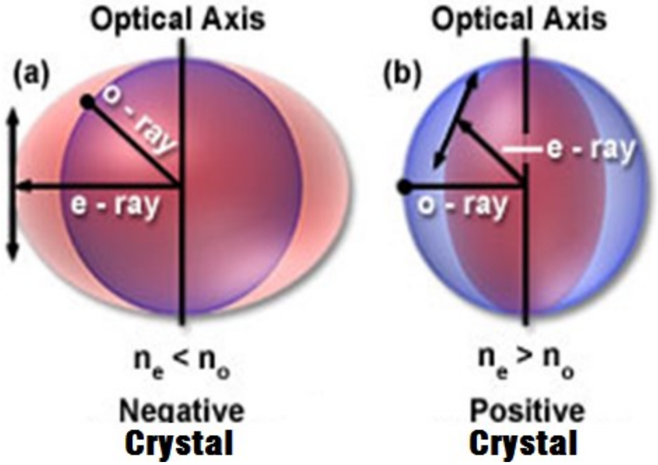
Positive crystals

Positive crystals are crystals in which refractive for O-Ray is less than that for E-Ray(n_0<n_E).

The velocity of O-Ray is greater than or equal to the velocity of E-Ray.

The ellipsoidal E-wavefront is entirely within the spherical O-wavefront.

Example : Quartz (SiO_2), Sellaite (MgF_2),Rutile (TiO_2),...



Optic axis

Optic axis of a crystal is the direction along which a ray of transmitted light suffers no birefringence (double refraction).

Light propagates along optic axis with a speed independent of its polarization.

According to number of optic axes crystals are divided as : Uniaxial and Biaxial crystals.

Phase retardation plate

A doubly refracting uniaxial crystal plate of uniform thickness having refracting surfaces parallel to direction of optic axis and capable of producing a definite phase difference between the ordinary and the extraordinary ray, is called phase retardation plate.

A retardation plate is an optically transparent material which resolves a beam of polarized light into two orthogonal components; retards the phase of one component relative to the other; then recombines the components into a single beam with new polarization characteristics.

If n_O & n_E are refractive indices of O-ray & E- ray respectively, λ is wavelength of light and t is the thickness of retardation plate.

Then,

Path difference between O-ray & E- ray can be given by

$$\Delta = t\,(n_O - n_E)$$

And phase difference between O-ray & E- ray can be given by

$$\delta = \frac{2\pi}{\lambda} t\,(n_O - n_E)$$

Types of retardation plates

1) Quarter wave plate
2) Half wave plate

1) Quarter wave plate

A doubly refracting uniaxial crystal plate having refracting faces parallel to the direction of the optic axis, having a thickness such that it creates a path difference of $\lambda/4$ or a phase difference of $\pi/2$ between the O-ray and the E-ray is called Quarter wave plate.

For quarter wave plate :

Path difference, $\Delta = t\,(n_O - n_E) = \lambda/4$

where λ is the wavelength of the incident light.

Thickness, $t = \frac{\lambda}{4(n_O - n_E)}$

Uses of quarter wave plate

If linearly polarized light is incident on a quarter-wave plate at 45° to the optic axis, then the light is divided into two equal electric field components. One of these is retarded by a quarter wavelength. This produces circularly polarized light.

If circularly polarized light is incident on quarter wave plate at 45° to the optic axis then it produces linearly polarized light.

If linearly polarized light is incident on quarter wave plate other than 45° to the optic axis then it produces elliptical polarized light.

2) Half wave plate

A doubly refracting uniaxial crystal plate having refractive faces parallel to the direction of the optic axis ,having a thickness such that it creates a path difference of $\lambda/2$ or a phase difference of π between the O-ray and the E-ray is called a Half wave plate.

For quarter wave plate:

Path difference, $\Delta = t(n_O - n_E) = \lambda/2$

where λ is the wavelength of the incident light.

Thickness, $t = \frac{\lambda}{2(n_O - n_E)}$

A retarder that produces a $\lambda/2$ phase shift is known as a half wave retarder.

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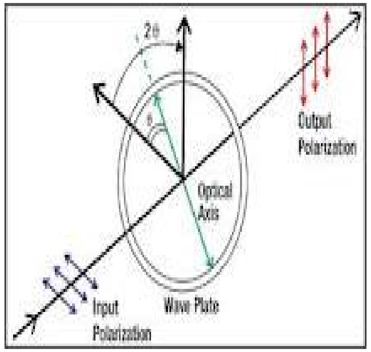
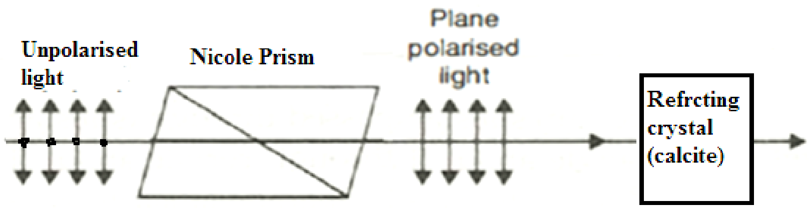
Use of half wave plate

Half wave retarders can rotate the polarization of linearly polarized light to twice the angle between the optic axis and the plane of polarization. Placing the optic axis of a half wave retarder at 45° to the polarization plane results in a polarization rotation of 90° to its original plane.



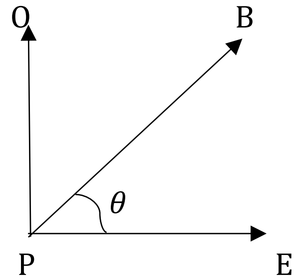
Analysis of polarised light



Let a monochromatic light is incident on nicole prism, after passing through it light is plane polarised and it is incident normally on double refracting crystal P (calcite or quartz).

The plane polarised light entering into the crystal is split up into two components that is ordinary and extra ordinary. Both light components travel along the same direction but with different velocities. Let t be the thickness of this crystal which produces phase difference δ between ordinary and extra ordinary ray.

Theory:



Suppose the amplitude of the incident plane polarised light in a crystal is A and it makes an angle θ with the optic axis. Therefore the amplitude of ordinary ray vibrating along PO is $Asin\theta$ and amplitude of extra ordinary ray vibrating along PE is $Acos\theta$. Since a phase difference δ is introduced between the two rays after passing through the thickness 't' of crystal , the rays coming out of the crystal can be represented in terms of two simple harmonic motions as

For extra ordinary ray, $x = Acos\theta \sin(\omega t + \delta)$

For ordinary ray, $y = Asin\theta \sin \omega t$

Let $Acos\theta = a \quad \& \quad Asin\theta = b$

$x = a\sin(\omega t + \delta)$ ……….(1)

$y = b\sin\omega t$ ………..(2)

From equation (2)

$\frac{y}{b} = \sin\omega t$ ……….(3)

$\cos\omega t = \sqrt{1 - \frac{y^2}{b^2}}$ ……….(4)

From equation (1)

$$\frac{x}{a} = \sin(\omega t + \delta)$$

$$\frac{x}{a} = \sin\omega t\cos\delta + \cos\omega t\sin\delta$$

From eq^n (3) & (4) above eq^n becomes

$$\frac{x}{a} = \frac{y}{b}\cos\delta + \sqrt{1 - \frac{y^2}{b^2}}\sin\delta$$

$$\frac{x}{a} - \frac{y}{b}\cos\delta = \sqrt{1 - \frac{y^2}{b^2}}\sin\delta$$

Squaring on both side, we get

$$\frac{x^2}{a^2} + \frac{y^2}{b^2}\cos^2\delta - \frac{2xy}{ab}\cos\delta = \left(1 - \frac{y^2}{b^2}\right)\sin^2\delta$$

$$\frac{x^2}{a^2} + \frac{y^2}{b^2}\cos^2\delta - \frac{2xy}{ab}\cos\delta = \sin^2\delta - \frac{y^2}{b^2}\sin^2\delta$$

$$\frac{x^2}{a^2} + \frac{y^2}{b^2}(\cos^2\delta + \sin^2\delta) - \frac{2xy}{ab}\cos\delta = \sin^2\delta \quad \ldots\ldots\ldots\ldots(5)$$

Special cases:

1) When $\delta = 0$

eq^n (5) becomes

$$\left(\frac{x}{a} - \frac{y}{b}\right)^2 = 0$$

$$\frac{y}{b} = \frac{x}{a}$$

$$y = \frac{b}{a}x$$

This gives the eq^n of straigh line . Therefore the emergent light is plane polarised.

2) When $\delta = \frac{\pi}{2}$ & $a \neq b$

eq^n (5) becomes

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} = 1$$

This represents the equation of a symmetrical ellipse. In this case the emergent light will be elliptically polarised provided $a \neq b$.

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3) When $\delta = \frac{\pi}{2}$ & $a = b$

eq^n (5) becomes

$x^2 + y^2 = a^2$

This represents the equation of circle of radius a. In this case the emergent light will be circularly polarised.

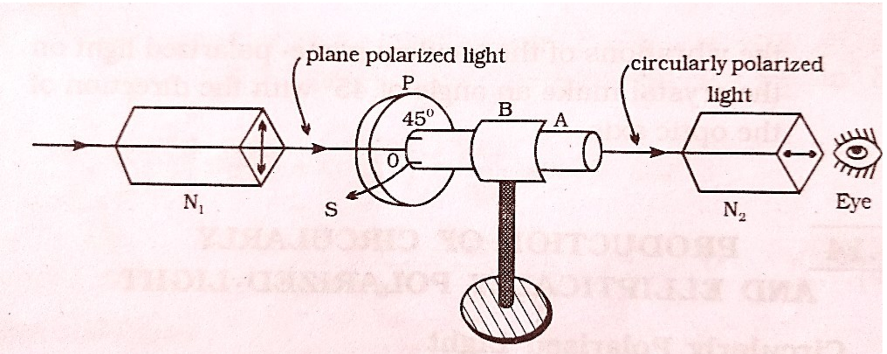
Here in this case, the vibration of plane polarised light on the crystal makes an angle 45^0 with the direction of the optic axis.

Production of polarised light

1) Plane polarised light

When monochromatic unpolarised light is allowed to fall on nicol prism. The beam after passing through it is plane polarised.

2) Circularly and elliptical polarised light



The nicol prism N_2 is kept at some distance from N_1 and N_2 is rotated such that no light will come out of it. A quarter wave plate P is mounted on a tube A. The tube A can rotate about outer fixed tube B introduced between N_1 and N_2.

Now the quarter wave plate is rotated such that no light come out of N_2, Keeping P fixed A is rotated such that mark S on P coincided with zero mark.

Now quarter wave plate P is rotated at all angles except 45^0 it produces elliptical polarised light and at exact 45^0 it produces circualrly polariised light.

Detection of Plane, Circularly and Elliptically Polarised Light

i) Plane Polarised Light

The light beam is allowed to fall on Nicol prism. If on rotation of Nicol prism, intensity of emitted light can be completely extinguished at two places in each rotation, then light is plane polarised.

ii) Circularly Polarised Light

The light beam is allowed to fall on a Nicol prism. If on rotation of Nicol prism the intensity of emitted light remains same, then light is either circularly polarised or unpolarised.

To differentiate between unpolarised and circularly polarised light, the light is first passed through quarter wave

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plate and then through Nicol prism. Because if beam is circularly polarised then after passing through quarter wave-plate an extra difference of λ/ 4 is introduced between ordinary and extraordinary component and gets converted into plane polarised.

Thus on rotating the Nicol, the light can.be extinguished at two plates.

If, on the other hand, the beam is unpolarised, it remains unpolarised after passing through quarter wave plate and on rotating the Nicol, there is no change in intensity of emitted light.

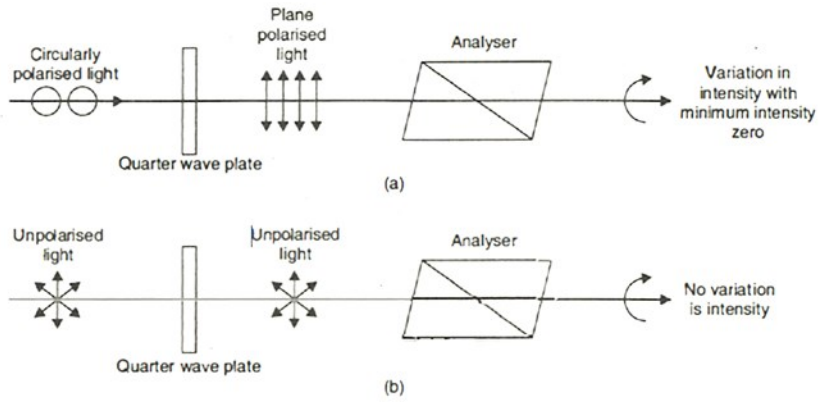

FIGURE 6.18

iii) Elliptically Polarised Light.

The light beam is allowed to fall on Nicol prism. If on rotation of Nicol prism the intensity of emitted light varies from maximum to minimum, then light is either elliptically polarised or a mixture of plane polarized and unpolarised.

To differentiate between the two, the light is first passed through quarter wave plate and then through Nicol prism. Because, if beam is elliptically polarised, then after passing through quarter wave plate, an extra path difference of λ/ 4 is introduced between 0-ray and E-ray and get converted into plane polarized

Thus, on rotating the Nicol, the light can be extinguished at two places.

On the other hand, if beam is mixture of polarised and unpolarised it remains mixture after passing through quarter wave plate and on rotating the Nicol intensity of emitted light varies from maximum to minimum.

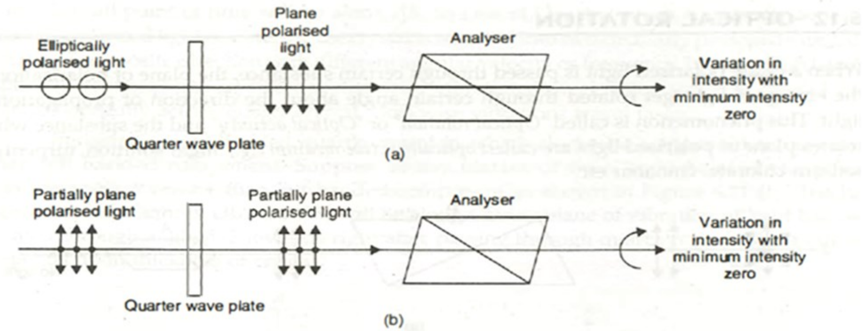

FIGURE 6.19

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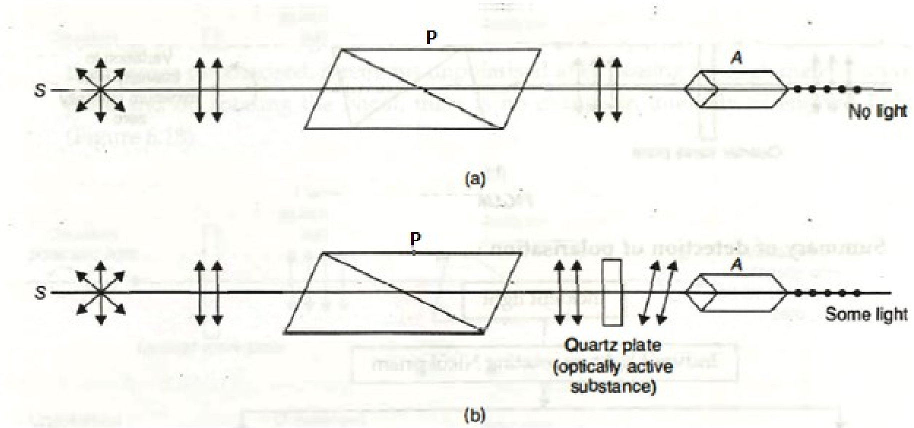
Optical Activity

The ability of substance (crystal or solution) to rotate plane of polarisation about the direction of light is called as optical activity.

The substance (crystal or solution) which can rotate plane polarised light is called as optical active substance.



There are two types of optically active substance

1) Dextro rotatory

The substance which rotates the plane of vibration in the clockwise with respect to the observer looking towards the source from the analyser is called as Dextro rotatory (right handed). Ex., Fruit Sugar , quartz crystal, etc.

2) Laevo Rotatory

The substance which rotates the plane of vibration in the anticlockwise with respect to the observer looking towards the source from the analyser is called as Laevo rotatory (left handed). Ex. Cane sugar solution

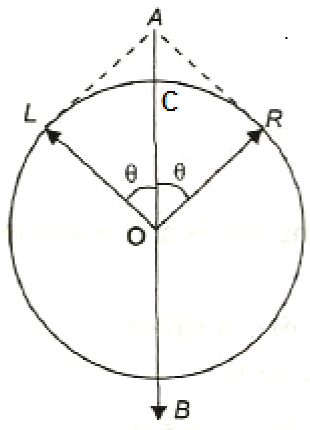
Fresnel's theory of optical rotation

To explain phenomenon of optical rotation, Fresnel made following assumptions;

1) When a plane polarised beam enters into optically active substance, it splits up into two opposite directed circularly polarised beams; one clockwise and another anticlockwise.
2) These two circularly polarised beams travels with the same velocity in an optically inactivity substances, but they travel with different velocities in an optically active substances.
3) On emerging out of the opticallly active substance, both circularly polarised beams recombine to form a plane polarised beam but its plane of vibration is rotated by certain angle direction of incident plane of vibration.

The amount of the angle of rotation depends on the phase difference between two circularly polarised beams in optical active substance.

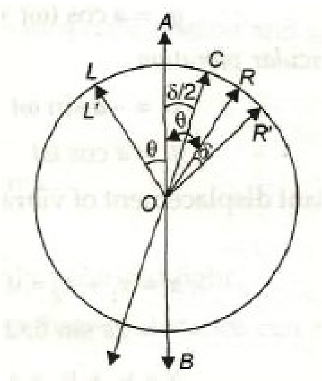
i) Optically inactive substance(Calcite)



Let a plane polarised light be incident on calcite along optical axis OCA. It splits up into two circularly polarised light vibrations rotating on opposite direction with the same angular velocity. Vibrations rotating in clockwise direction are represented by OR and vibration rotating in anticlockwise direction are represented by OL .At any instant they have same angular displacement from OC therefore resultant of OR and OL at any time will be along OCA. Thus When light comes out of optically inactive substance they recombine forming plane polarised light whose vibration will be along OCA.

ii) Optically active substance (Quartz crystal)

In case of Quartz (optically active), a linearly polarised light on entering the crystal is resolved into two circularly polarised vibrations rotating in opposite direction with different angular velocity or frequency. Consider a right handed quartz crystal in which clockwise component travels faster than left handed component.



Suppose at any instant of time, right handed component rotated by an angle δ greater than left handed component as shown in Figure. The new position of resultant of OL' and OR' will be along CO i.e., plane of vibration of light has been rotated through angle δ/2 towards right after passing through quartz crystal. The angle δ/2 depends upon thickness of crystal.

Analytical treatment

a) **For calcite crystal which is optically inactive**:

when linearly plane polarised light enters a calcite crystal it get resolved into two circularly polarised vibrations. One is moving anticlockwise other in clockwise direction with same angular frequency or velocity. As each circularly polarised vibration further consist of two rectangular components having zero phase differences.

So, for clockwise circular vibration

$$x_1 = a\,sin\theta = a\,sin\,\omega t$$

$$y_1 = a\cos\theta = a\cos\omega t$$

For anticlockwise circular vibration

$$x_2 = -a\,sin\theta = -a\,sin\,\omega t$$

$$y_2 = a\cos\theta = a\cos\omega t$$

From above, the resultant displacement of vibrations along x-axis and y-axis respectively are given as,

$$x = x_1 + x_2 = a \sin\theta - a \sin\theta = 0$$

$$y = y_1 + y_2 = a \cos\omega t + a \cos\omega t = 2\, a \cos\omega t$$

Hence resultant vibration has amplitude 2a and its plane is y-axis i.e., along original direction ACB. Hence two oppositely circularly polarised vibrations give rise to a plane polarised vibrations.

(b) **For quartz crystal which is optically active**:

When linearly plane polarised light enters quartz crystal (right handed), it gets resolved into circularly polarised vibrations moving in opposite direction with different angular frequency or velocity. In case of right handed crystal clockwise vibrations travel faster than anticlockwise vibrations. Let at any instant of time anticlockwise vibrations has traversed angle θ and clockwise vibrations has traversed angle $(\theta + \delta)$. Therefore, component of two circular vibrations at that instant of time will be,

For clockwise vibration

$$x_1 = a \sin(\omega t + \delta)$$

$$y_1 = a \cos(\omega t + \delta)$$

For anticlockwise circular vibration

$$x_2 = -\, a \sin\omega t$$

$$y_2 = a \cos\omega t$$

From resultant displacement of vibrations along x-axis and y-axis respectively are given as,

$$x = x_1 + x_2 = a \sin(\omega t + \delta) - a \sin\omega t$$

$$x = 2a \sin\delta/2 \cos(\omega t + \delta/2) \quad \ldots\ldots\ldots\ldots(1)$$

$$y = y_1 + y_2 = a \cos(\omega t + \delta) + a \cos\omega t$$

$$y = 2a \cos\delta/2 \cos(\omega t + \delta/2) \quad \ldots\ldots\ldots\ldots(2)$$

The resultant vibration along x-axis and y-axis are in same phase, so resultant of these vibrations is plane polarised and makes an angle of δ/2 with original direction AB. Thus, plane of vibrations get rotated through angle δ/2 towards right after passing through a right handed quartz crystal.

Dividing Eq^n (2) by Eq^n (1), we get

$$\tan\frac{\delta}{2} = {}^{x}\!/_{y}$$

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Angle of Rotation

If μ_R ,μ_L be the refractive indices of quartz crystal for right handed and left handed vibrations respectively ($\mu_L > \mu_R$) then optical path difference on passing through a quartz crystal slab of thickness 't' is given as,

Path difference = $(\mu_L - \mu_R)\, t$

If λ be the wavelength of light used, then phase difference,

$$\delta = \frac{2\pi}{\lambda} (\mu_L - \mu_R)\, t.$$

Angle of rotation

$$\frac{\delta}{2} = \frac{\pi}{\lambda} (\mu_L - \mu_R)\, t$$

In case of left handed optically active crystals, ($\mu_R > \mu_L$)

$$\frac{\delta}{2} = \frac{\pi}{\lambda} (\mu_R - \mu_L)\, t$$

Specific Rotation

When a linearly plane polarised light is passed through an optically active medium/ substance, the plane of vibration of linearly polarised light get rotated tuhrough certain angle either towards left or right. The angle through which plane polarised light get rotated depends upon

(i) Thickness of the medium
(ii) Density of active substance or concentration of solution
(iii) Wavelength of light
(iv)Temperature.

The rotation of plane of vibration produced by solution of unit length and unit concentration at given temperature for given wavelength is known as specific rotation

Specific rotation, $S = \frac{\theta}{LC}$

Where θ = angle of rotation, L = length of solution (tube), C = concentration of solution.

The rotation produced by optically active/medium/substance can be measured by polarimeter.

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