DYAL SINGH COLLEGE, UNIVERSITY OF DELHI

(E-RESOURCE MATERIAL / STUDY MATERIAL)

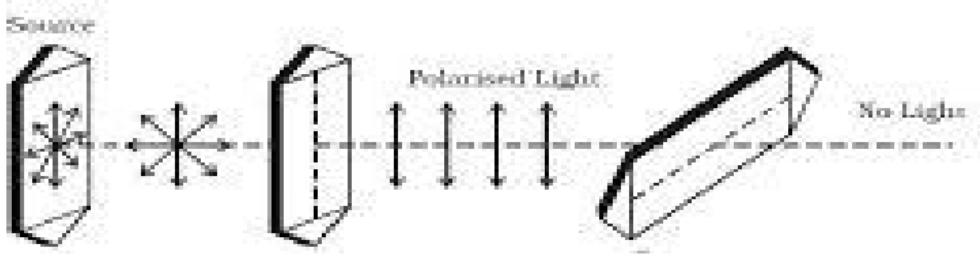
Paper Name: B.Sc, Physical Sciences, Sem- IV, Sec-C, Wave and Optics

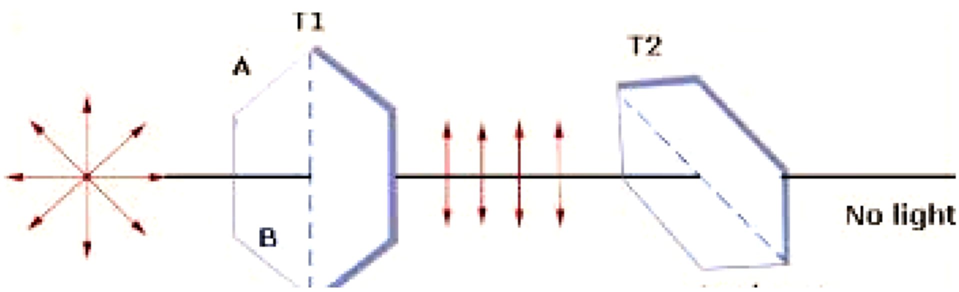
Teacher's Name- Dr. Monika Gupta (Physics Deptt.)

POLARISATION (Part-1)

The phenomenon of restricting the vibration of light in a particular direction perpendicular to the direction of wave motion is called as polarisation.

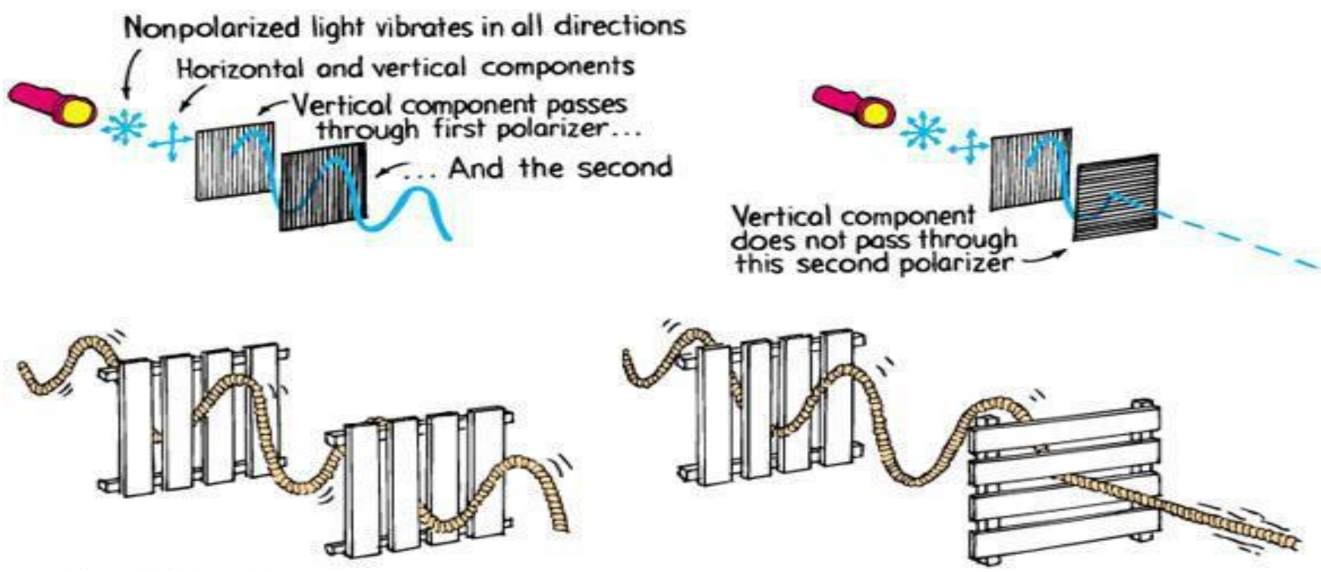
To explain the phenomenon of polarisation let us consider the two tourmaline crystal with their optics axis placed parallel to each other .When an ordinary light is incident normally on the two crystal plates the emergence light shows a variation in intensity as T_2 is rotated.





The intensity is maximum when the axis of T_2 is parallel to that of T_1 and minimum when they are at right angle. This shows that the light emerging from T_1 is not symmetrical about the direction of propagation of light but its vibration are confined only to a single line in a plane perpendicular to the direction of propagation, such light is called as polarised light.

Example:



Difference between Polarised and ordinary light:

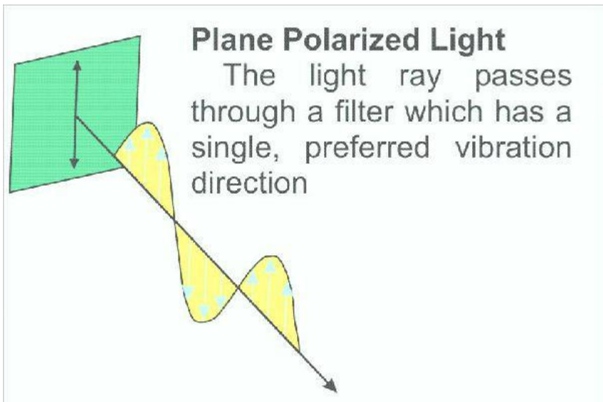
Polarised light	Ordinary light
1. The vibrations are confined in a particular direction. 2. The probability of occurrence of vibration along the axis of crystal is not same in all position of crystal 3. The intensity of light plate is not same in all position of the crystal plate.	1. The vibrations of light particle are not confined in a particular direction. 2. The probability of occurrence of vibration along the axis of the crystal is not symmetries for all position of the crystal. 3. The intensity of light plate is same in all position of the plate.

Polarised light:

The resultant light wave in which the vibrations are confined in a particular direction of propagation of light wave, such light waves are called Polarised light. Depending on the mode of vibration in a particular direction, the polarised light is three types:-

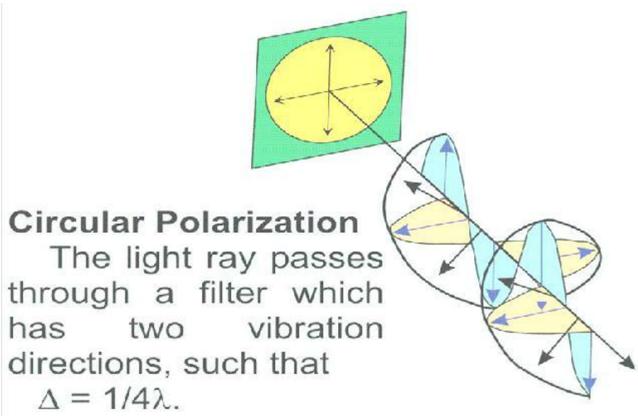
Linearly Polarised /Plane polarised:

When the vibrations are confined to a single linear direction at right angles to the direction of propagation, such light is called Plane polarised light.



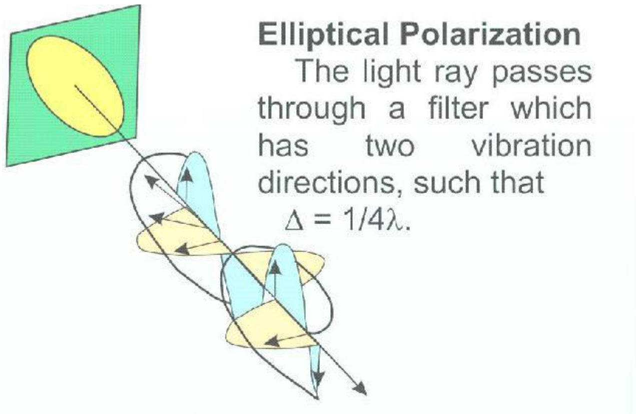
Circularly polarised light:

When the two plane polarised wave superpose under certain condition such that the resultant light vector rotate with a constant magnitude in a plane perpendicular to the direction of propagation and tip of light vector traces a circle around a fixed point such light is called circularly polarised light.



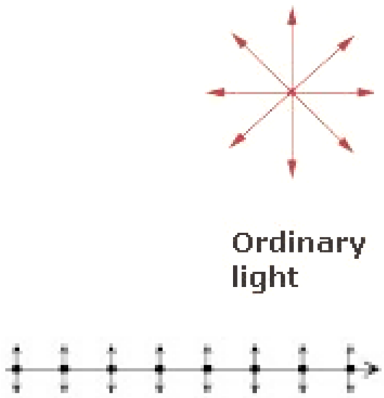
Elliptically polarised light:

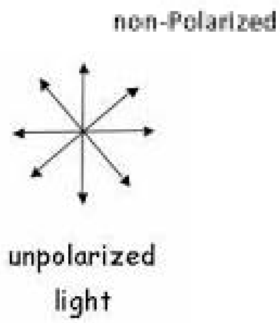
When two plane polarised light are superpose in such a way that the magnitude of the resultant light vector varies periodically during its rotation then the tip of the vector traces an ellipse such light is called elliptically polarised light.



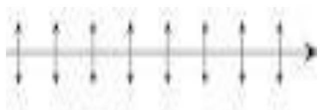
Pictorial representation of polarised light:

Since in unpolarised light all the direction of vibration at right angles to that of propagation of light. Hence it is represented by star symbol.





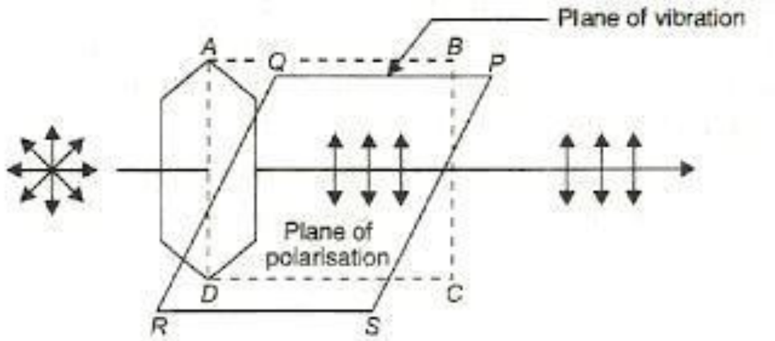
In a plane polarised beam of light, the polarisation is along straight line, the vibration are parallel to the plane and can be represented by



If the light particles vibrate along the straight line perpendicular to the plane of paper, then they can be represented by a dot.

Plane of vibration:

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



Plane of polarisation:

The plane passing through the direction of propagation and containing no vibration is called as plane of polarisation.

Since a vibration has no component of right angle, to its own direction, so the plane of polarisation is always perpendicular to the plane of vibrations. Angle between plane of vibration and plane of polarisation is 90˚.

Light waves are transverse in nature:

If the light waves are longitudinal in nature, they will show no variation of intensity during the rotation of the crystal. Since during the rotation of the crystal, the variation in intensity takes place, this suggests that light waves are transverse in nature rather longitudinal.

Production of plane polarised light:

The plane polarised light can be produced in four different ways such as

1. Polarisation by Reflection

2. Polarisation by Refraction

3. Polarisation by Scattering

4. Polarisation by Double refraction

1. Polarisation by reflection:

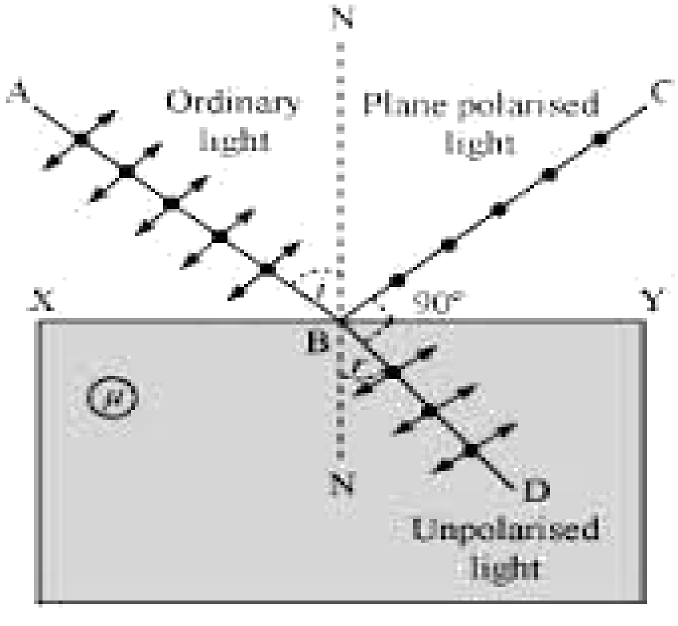
The production of the polarised light by the method of reflection from reflecting interface is called polarisation by reflection.

When the unpolarised light incident on a surface, the reflected light may be completely polarised, partially polarised or unpolarised depending upon the angle of incidence. If the angle of incidence is 0° or 90° the light is not polarised. If the angle of incidence lies in between 0° and 90°, the light is completely plane polarised.

The angle of incidence for which the reflected component of light is completely plane polarised, such angle of incidence is called polarising angle or angle of polarisation or Brewster's angle .It is denoted by i_p.

At i_p the angle between reflected ray and refracted or transmitted ray is $\pi/2$.

Explanation: To explain the polarisation by reflection, let us consider an interface XY on which a ray AB which is unpolarised is incident at an angle equal to polarising angle and get reflected along BC which is completely plane polarised and the ray BD which is refracted or transmitted is continues to be unpolarised. The incident unpolarised light contain both perpendicular and parallel component of light.



The parallel component of light is converted into perpendicular component and gets reflected from the interface. The parallel component of light is continues to vibrate and get refracted or transmitted. As a result of which the reflected component is polarised.

Conclusion:

Hence, the reflected ray of light contains the vibrations of electric vector perpendicular to the plane incidence. Thus the reflected light is completely plane polarised perpendicular to plane of incidence.

Brewster's Law:

This law states that when an unpolarised light is incident at polarizing angle "i_p" on an interface separating air from a medium of refractive index "μ" then the reflected light is fully polarized. i.e. $\mu = \tan i_p$

To explain Brewster's law, let XY be a reflecting surface on which;

AB = unpolarised incident light

BC= completely polarized

BD = partially polarized

i_p =angle of incidence, angle of polarization

From fig.

$\angle$CBY+ $\angle$ DBY=90°

$$\left(90^0 - r'\right) + \left(90^0 - r\right) = 90^0$$

$$\Rightarrow \left(90^0 - i_p\right) + \left(90^0 - r\right) = 90^0$$

$$\Rightarrow i_p + r = 90^0$$

$$\Rightarrow r' = 90^0 - r$$

From Snell's law

$$\mu = \frac{\sin i_p}{\sin r} = \frac{\sin i_p}{\sin(90^0 - i_p)} = \frac{\sin i_p}{\cos i_p} = \tan i_p$$

Thus the tangent of the angle of polarization is numerically equal to the refractive index of the medium.

NOTE: We can also prove in case of reflection at Brewster's angle reflected and refracted ray are mutually perpendicular to each other.

From Brewster's law;

We have $\mu = \tan i_p = \dfrac{\sin i_p}{\cos i_p}$

According to Snell's law;

$$\mu = \frac{\sin i_p}{\sin r}$$

From above equations

$$\sin r = \cos i_p \Rightarrow \sin r = \sin(90^0 - i_p) \Rightarrow r = 90^0 - i_p \Rightarrow r + i_p = 90^0$$

$$\Rightarrow \quad 90^0 - \angle CBY + 90^0 - \angle DBY = 90^0$$

$$\Rightarrow \quad \angle CBY + \angle DBY = 90^\circ$$

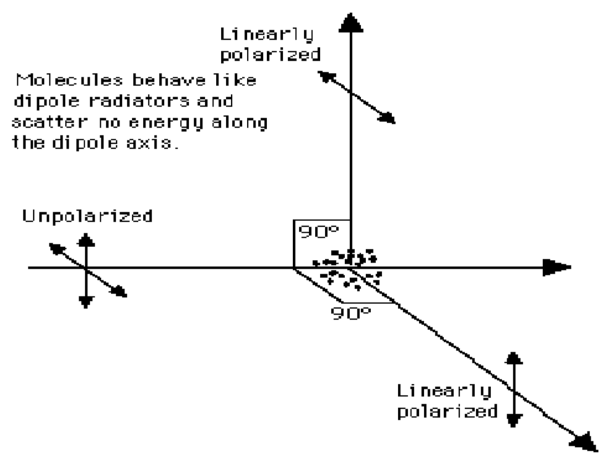
$$\Rightarrow \quad CB \perp BD \Rightarrow \angle CBD = 90^0$$

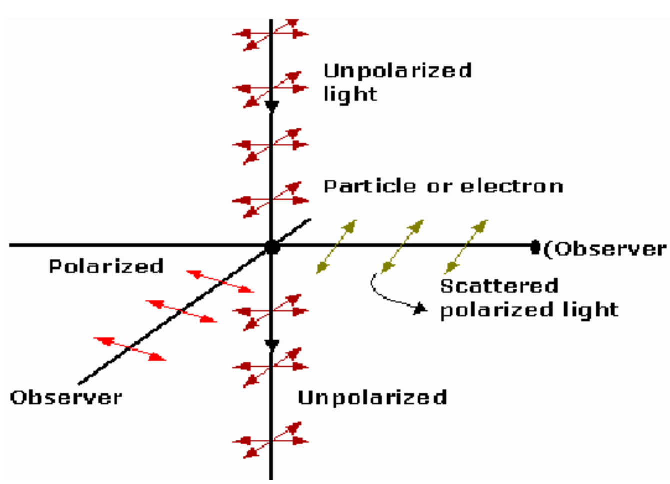
Thus, it is concluded that at polarizing angle or at Brewster's angle, the reflected light and the refracted light are mutually perpendicular to each other.

2. Polarisation by Scattering:

When a beam of ordinary light is passed through a medium containing particles, whose size is of order of wavelength of the incident light, then the beam of light get scattered in which the light particles are found to vibrate in one particular direction. This phenomenon is called "Polarisation by scattering".

Explanation:

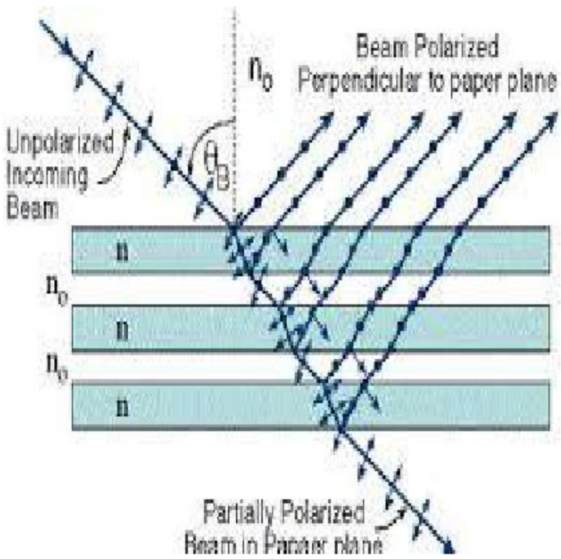


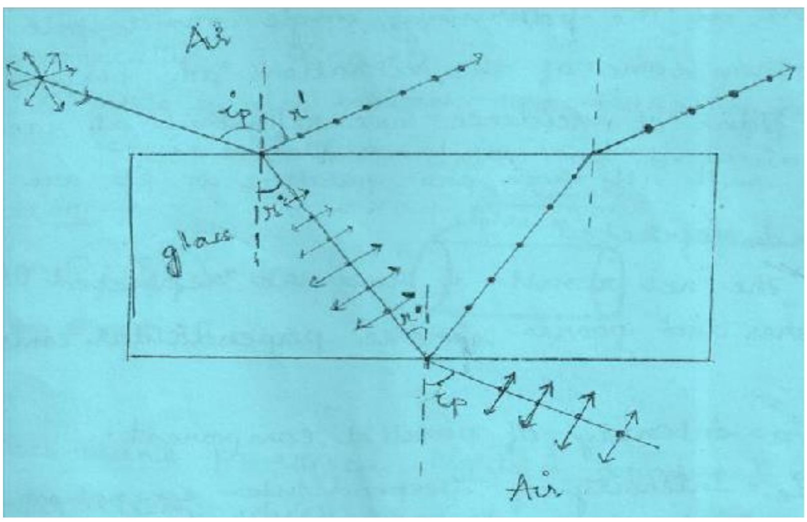


To explain the phenomenon of scattering, let us consider a beam of unpolarised light along z-axis on a scatter at origin. As light waves are transverse in nature in all possible direction of vibration of unpolarised light is confined to X-Y plane. When we look along X-axis we can see the vibrations which are parallel to Y-axis. Similarly, when we look along Y-axis the vibration along X-axis can be seen. Hence, the light can be scattered perpendicular to incident light is always plane polarized.

Polarisation by refraction:

The phenomenon of production of polarised light by the method of refraction is known as polarisation by refraction.





To explain the polarization by refraction, let us consider an ordinary light which is incident upon the upper surface of the glass slab at an polarizing angle i_p or Brewster's angle θ_B , so that the reflected light is completely polarized while the rest is refracted and partially polarized. The refracted light is incident at the lower face at an angle "r".

Now,

$$\tan r = \frac{\sin r}{\cos r} = \frac{\sin r}{\sin(90^0 - r)} = \frac{\sin r}{\sin i_p} = {}^g\mu_a \quad \Rightarrow \tan r = {}^g\mu_a$$

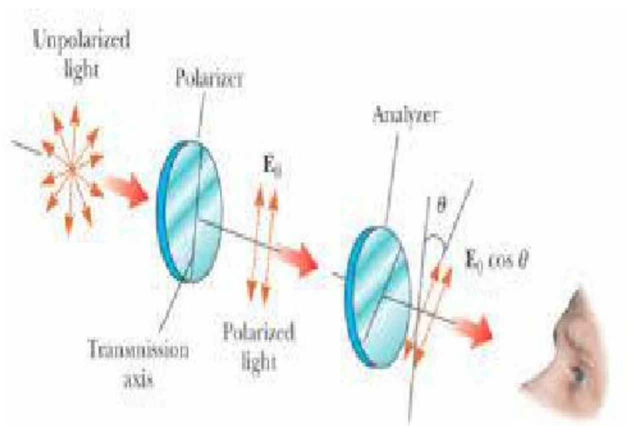
Thus according to Brewster's law, "r" is the polarizing angle for the reflection at the lower surface of the plate. Hence, the light reflected at the lower surface is completely plane-polarised, while that transmitted part is partially polarised. Hence, if a beam of unpolarised light be incident at the polarizing angle on a pile of plates, then some of the vibrations are perpendicular to the plane of incidence are reflected at each surface and all those parallel to it are refracted. The
net result is that the refracted beams are poorer and poorer in the perpendicular component and less partially polarised component.

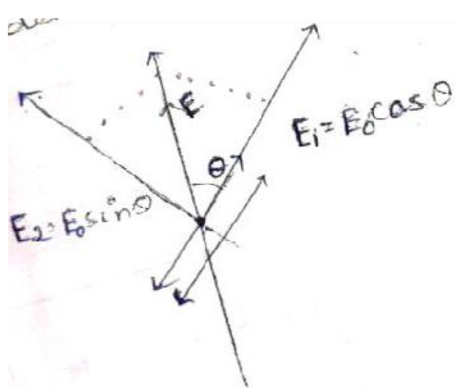
Malus' law:

It states that when a beam of completely plane polarized light incident on the plane of analyser, the intensity of the transmitted light varies directly proportional to the square of the cosine of the angle between the planes of the polariser and plane of the analyser.

Mathematically,

$$I \alpha \cos^2 \theta$$





Proof:

Let us consider a beam of plane polarised light coming from the plane of the polariser is incident at an angle "θ" on the plane of the analyser. The amplitude of the light vector "E" is now resolved into two mutual perpendicular component i.e. $E_1 = E_0 \cos\theta$ which is parallel to the plane of transmission and $E_2 = E_0 \sin\theta$ which is perpendicular to the plane of transmission. As we are able to see only the parallel component so the intensity of the transmitted light coming from the plane of the analyser is proportional to the parallel component only.

Thus,

$$I \alpha E_1^2 \Rightarrow I = kE_0^2 \cos^2\theta = I_0 \cos^2\theta \text{ , where } I_0 = kE_0^2$$

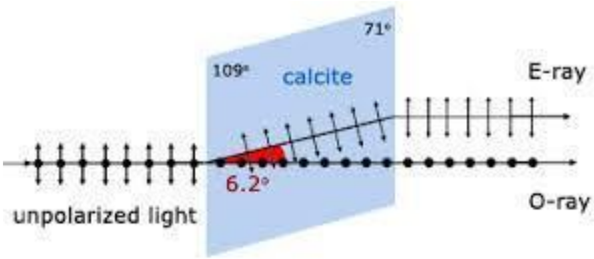
$$\Rightarrow I \alpha \cos^2\theta \quad \text{which is Malus's law}$$

Double refraction:

The phenomenon of splitting of ordinary light into two refracted ray namely ordinary and extra ordinary ray on passing through a double refracting crystal is known as double refraction

Explanation:

To explain the double refraction, let us consider an ordinary light incident upon section of a doubly refracting crystal



When the light passing through the crystal along the optic axis then at the optic axis the ray splits up into two rays called as ordinary and extraordinary ray which get emerge parallel from the opposite face of the crystal through which are relatively displaced by a distance proportional to the thickness of the crystal. This phenomenon is called as double refraction.

Difference between ordinary (O-ray) and Extra ordinary ray (E-ray)

Ordinary ray	Extra Ordinary ray
1.These ray obeys the law of refraction	1. These ray do not obey law of refraction
2.For ordinary ray plane of vibration lies perpendicular to the direction of propagation	2.For extraordinary ray the plane of vibration parallel to the direction of propagation
3.The vibration of particles are perpendicular to the direction of ray.	3. The vibration of particle is parallel to the direction of ray.
4. Plane of polarisation lies in the principal plane.	4. Plane of polarisation is perpendicular to its principal axis.
5. Refractive index is constant along optics axis.	5. Refractive index varies along Optics axis.
6. It travels with the constant speed in all direction.	6.It travels with different speed in different direction .But it travel with equal speed along optics axis

Double refracting crystal:

The crystal which splits a ray of light incident on it into two refracted rays such crystal are called double refracting crystal.It is of two types

1. Uniaxial
2. Biaxial.

Uniaxial: The double refracting crystal which have one optic axis along which the two refracted rays travel with same velocity are known as uniaxial crystal

Ex: Calcite crystal, tourmaline crystal, quartz

Biaxial: The double refracting crystal which have two optic axis are called as biaxial crystal

Ex: Topaz, Agromite

Optic axis: It is a direction inside a double refracting crystal along which both the refracted behave like in all respect.

Principal section: A plane passing through the optic axis and normal to a crystal surface is called a principal section

Principal plane:

The plane in the crystal drawn through the optic axis and ordinary ray or drawn through the optic axis and the extraordinary ray is called as principal plane these are two principal plane corresponding to refracted ray.

Polarisation by double refraction:

To explain polarisation by double refraction let us consider a beam of light incident normally through a pair of calcite crystal and rotating the second crystal about the incident ray as axis we have the following situations as:

Case 1

When principal sections of two crystals are parallel then two images O_1 and E_1 are seen. The ordinary ray from the first crystal passes undeviated through the 2^{nd} crystal and merges as O_1 ray. The extraordinary ray (E-ray) from the 1st crystal passes through the 2^{nd} crystal along a path parallel to that inside the 1^{st} and emerges as E_1-ray. Hence the image O_1 and E_1 are seen separately.

Case 2

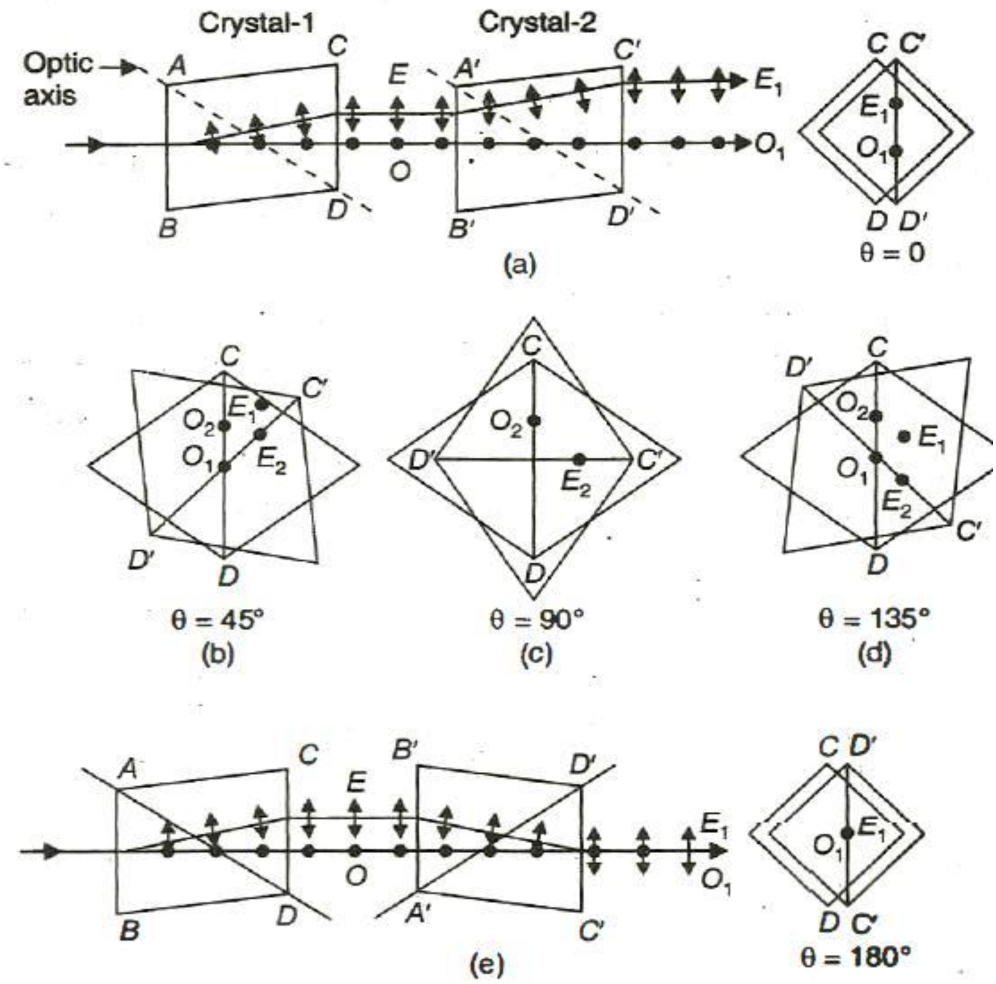
When the 2nd crystal is rotated through an angle 45° with respect to 1st, then the two new images O_2 and E_2 appear. As the rotation is continued, O_1 and O_2 remained fixed while E_1 and E_2 rotate around O_1 and O_2 respectively and images are found to be equal intensities.

Case 3

When the 2nd crystal is rotated at an angle 90° w.r.t 1st the original images O_1 and E_1 have to vanish and all the new images O_2 and E_2 have acquired the maximum intensity.

- When the 2nd crystal is rotated at an angle 135° w.r.t the 1st, four images once again appear with equally intense.

- When the 2nd crystal is rotated at an angle 180° w.r.t 1st, the O_2 and E_2 vanishes and O_1 and E_1have come together in the centre.



This is how we are able to produce the plane polarised light by the method of double refraction.