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POLARISATION OF LIGHT

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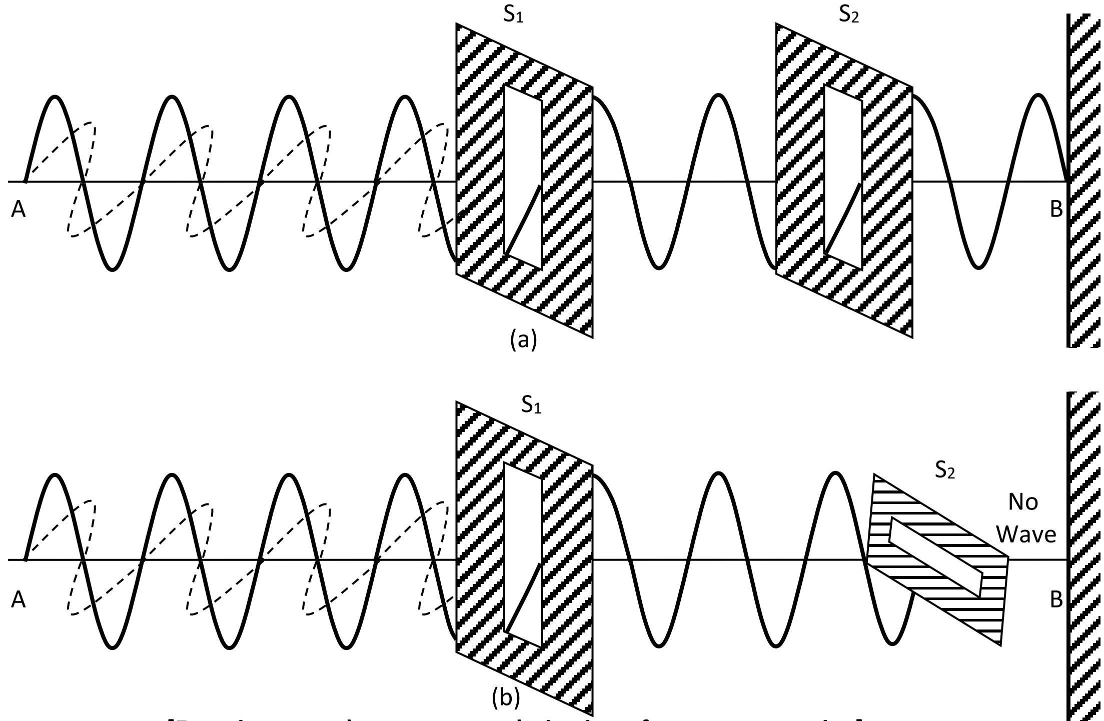
POLARISATION OF WAVES:

The waves are of two types: Transverse and Longitudinal. Both types of these waves undergo reflection, refraction, interference and diffraction. The difference is that only transverse waves can be polarised.

A transverse wave in which vibrations are present in all possible directions, in a plane perpendicular to the direction of propagation, is said to be unpolarised. If the vibrations of a wave are present in just one direction in a plane perpendicular to the direction of propagation, the wave is said to be polarised or plane polarised. The phenomenon of restricting the oscillations of a wave to just one direction in the transverse plane is called polarisation of waves.

Experimental demonstration with mechanical waves: Consider a long string AB passing through two rectangular slits S_1 and S_2, as shown in Fig. The end B of the string is tied to a hook in a wall and the free end A is jerked in all possible directions perpendicular to the length of the string so as to generate transverse waves in it. The portion AS_1 of the string has vibrations in all directions perpendicular to AB, so that the wave is unpolarised. The first slit S_1 will permit only those vibrations to pass through it which are parallel to the slit S_1 and will cut of all other vibrations. Thus the wave emerging from the slit S_1 is plane polarised. The slit S_1 is called the polariser. If the second slit S_2, called the analyser, is held parallel to S_1, the wave from S_1 will pass through S_2 unchanged. If S_2 is held perpendicular to S_1, no vibrations will emerge from the slit S_2. This indicates that the slit S_1 has polarised the incoming wave in the vertical plane.

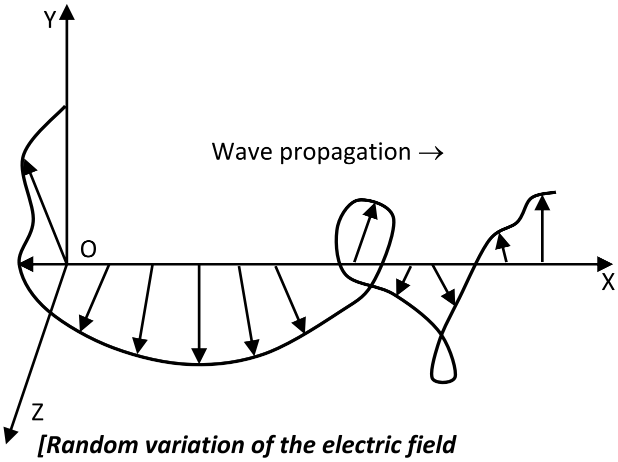


[Experiment to demonstrate polarisation of a wave on a string]

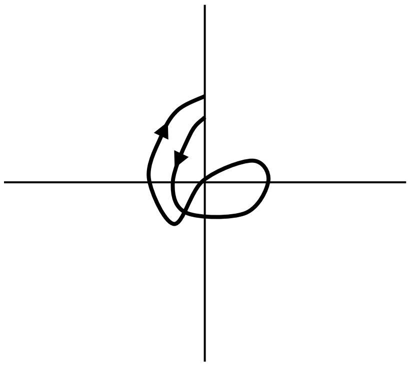
Longitudinal waves cannot be polarised: This is because these waves are symmetrical about the direction of propagation. For example, if we pass a long spring through two slits and generate a longitudinal wave in it by alternately compressing and releasing its free end, it is seen that the compressions and rarefactions pass through the two slits, whatever is their relative orientation. This is so because the oscillations occur along the length of the spring, i.e., along the direction of the wave propagation. On the other hand, the transverse waves can be polarised as they do not show any symmetry about the direction of wave propagation.

UNPOLARISED AND PLANE POLARISED LIGHT

Unpolarised light: In ordinary light, electric field vector vibrates in all directions in a plane perpendicular to the directions of propagation. A light which has vibrations in all directions in a plane perpendicular to the direction of propagation. A light which has vibrations in all directions in a plane perpendicular to the direction of propagation is said to be unpolarised light. The light from the sun, a sodium lamp, an incandescent bulb or a candle is unpolarised. The electric field vector of such a light takes all possible directions in the transverse plane, rapidly and randomly, during the time of measurement, as shown in Fig. The tip of the electric field vector traces an irregular curve, as shown in Fig.



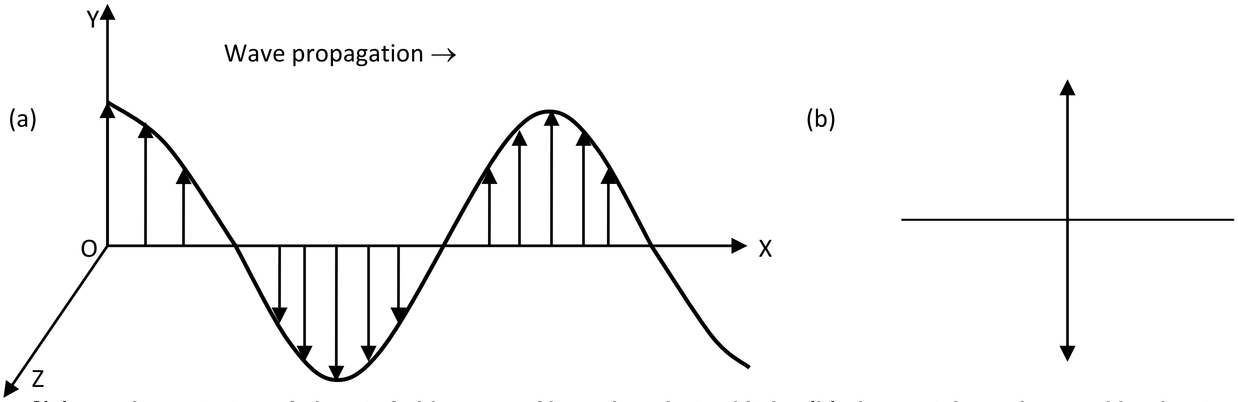
[Random variation of the electric field vector of unpolarised light]



[Irregular curve traced by the tip of this vector]

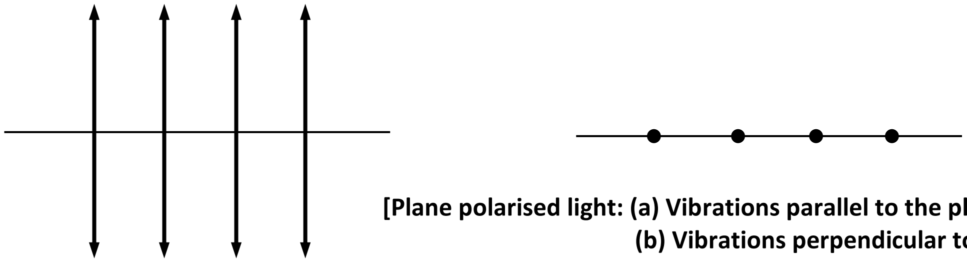
Fig. (a) is the pictorial representation of unpolarised light propagation out of the plane of paper. It shows vibrations in all directions in the transverse plane. Fig. (b) is also a pictorial representation of an unpolarised light. Here double arrows represent the vibrations in the plane of paper and small dots represent vibrations perpendicular to the plane of paper.

Plane of polarised or linearly polarised light: If the electric field vector of a light wave vibrates just in one direction perpendicular to the direction of wave propagation, then it is said to be ***linearly polarised***. Since in a linearly polarised. Since in a linearly polarised wave, the vibrations at all points, at all times, lie in the same plane, so it is also called a ***plane polarised wave***. Fig. (a) shows the regular variation of the electric field vector of a linearly [polarised light along Y-axis. Its tip vibrates back and forth along a straight line [Fig. (b)]



[(a) Regular variation of electric field vector of linearly polarised light. (b) The straight path traced by the tip of this vector]

Fig. (a) and (b) show the pictorial representations for polarised right.



**[Plane polarised light: (a) Vibrations parallel to the plane of paper.
(b) Vibrations perpendicular to the plane of paper.]**

POLARISERS

A device that plane-polarisers the unpolarised light passed through it is called a polariser.

Some commonly used polarisers are as follows:

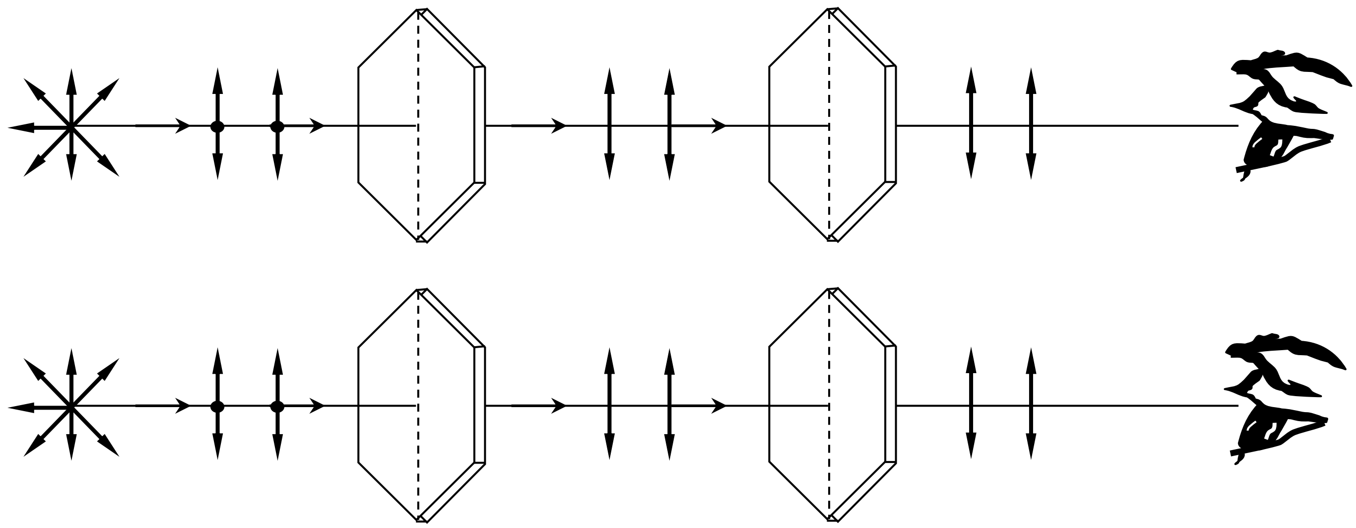
1. Tourmaline crystal: The tourmaline crystal is so cut that its plane contains its optic axis. When unpolarised light is incident on it normally, it allows only such electric field vibrations to pass through it which are parallel to its axis. Such a crystal can be used to polarise a beam of unpolarised light.

2. Nicol prism: It is an optical device used for producing and analysing plane polarised light. It consists of two pieces of calcite suitably cut and stuck together with Canada balsam.

3. Polaroid: A Polaroid is a thin commercial sheet in the form of circular disc which makes use of the property of selective absorption to produce an intense beam of plane polarised light.

EXPERIMENT TO DEMONSTRATE POLARISATION OF LIGHT

Polarisation of light waves: As shown in Fig., when ordinary (unpolarised) light is passed through a tourmaline crystal P, its



intensity is cut down to half. Rotate the crystal P about the incident beam. There is no effect on the intensity of the transmitted beam. Now, if a similar crystal A is placed with its axis parallel to that of P, all the light transmitted by P also passes through A. However, as A is rotated from this position in its own plane, the intensity of light transmitted by its goes on decreasing until it becomes zero, when the axes of the two crystals are then said to be in the ***crossed position***. In one full rotation of A, the intensity of light becomes twice maximum and twice zero.

Clearly, the light transmitted by crystal P is polarised as it contains vibrations parallel to the axis of P. When the axis of A is parallel to that of P, the polarised beam passes as such through A also. But when the axis of A is perpendicular to that of P, the vibrations of the waves (being perpendicular to the axis of A) are not transmitted by A. The first crystal P which polarises the light is called polariser and the second crystal is called the analyser, because it analyses whether the light is polarised or not.

Since the polarisation of light can neither be explained on the basis of corpuscular theory of light nor by assuming that light propagates as longitudinal waves, therefore, the above experiment proves that light propagates in the form of transverse waves.

LAW OF MALUS

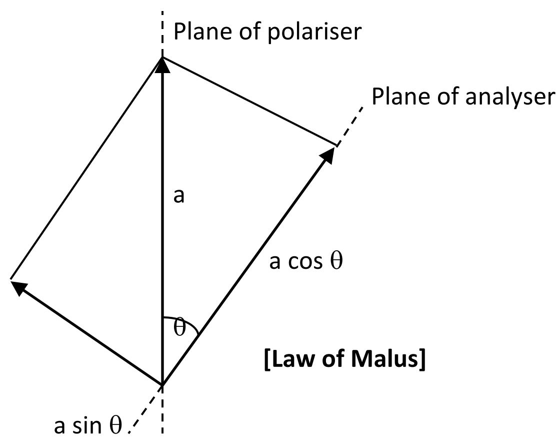
Law of Malus: When a plane polarised light is seen through an analyser, the intensity of transmitted light varies as the analyser, the intensity of transmitted light varies as the analyser is rotated in its own plane about the incident direction. In 1809, E.N. Malus discovered that when a beam of completely plane polarised light is passed through analyser, the intensity 'I' of transmitted light varies directly as the square of the cosine of the angle 'θ' between the transmission directions of polariser and analyser. This statement is know as the law of ***Malus***.

Mathematically,

$$I \propto \cos^2\theta \qquad \text{or} \qquad I = I_0 \cos^2\theta$$

Here I_0 is the maximum intensity of transmitted light. It may be noted that I_0 is equal to half the intensity of unpolarised light incident on the polariser.

Explanation of the law: As shown in Fig., suppose that the planes of polariser and analyser are inclined to each other at an angle θ. Let I_0 be the intensity and the amplitude of the plane polarised light transmitted by the polariser.



[Law of Malus]

The amplitude a of a light incident on the analyser has two rectangular components:
1. a cos θ, parallel to the plane of transmission of the analyser, and
2. a sin θ, perpendicular to the plane of transmission of the analyser.
So only the component a cos θ is transmitted by the analyser. The intensity of light transmitted by the analyser is

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

$= ka^2\cos^2\theta$

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

where $I_0 = ka^2$, is the maximum intensity of light transmitted by the analyser (when θ = 0°). The above equation is the law of Malus.

SPECIAL CASES:

1. When θ = 0° or 180°

$\cos\theta = \pm 1$, so that

$I = I_0$

So, when the transmission directions of polariser and analyser are parallel or antiparallel to each other, the maximum intensity of plane polarised light is transmitted by the analyser and is equal to the intensity emerging from the polariser.

2. When θ = 90°,

$\cos\theta = 0$, so that

$I = 0$

So, when the transmission directions of polariser and analyser are perpendicular to each other, the intensity of light transmission through the analyser is zero.

3. When a beam of unpolarised light is incident on the polariser,

$I = I_0\overline{\cos^2\theta}$

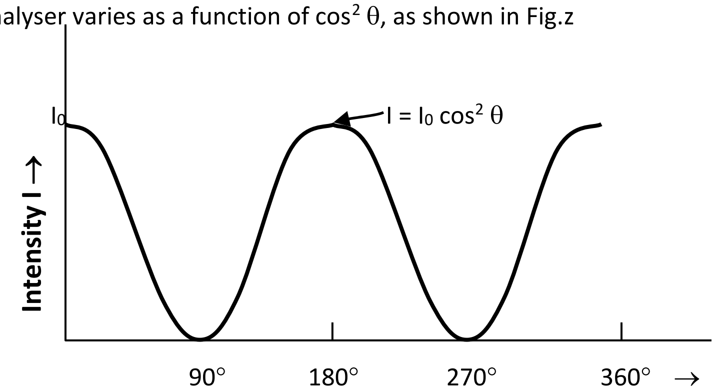
$= I_0 \times \frac{1}{2}\overline{(1+\cos 2\theta)}$

$= \frac{1}{2}I_0(1+\overline{\cos 2\theta})$

$= \frac{1}{2}I_0(1+0)$

$= \frac{1}{2}I_0$

Intensity curve: As the angle 'θ' between the transmission directions of polariser and analyser is varied, the intensity 'I' of the light transmitted by the analyser varies as a function of $\cos^2\theta$, as shown in Fig.z



[Graph of intensity I through analyser versus angle θ between polariser and analyser]

Examples based on the Law of Malus

◆ **FORMULA USED**

Law of Malus, $I = I_0\cos^2\theta$

◆ **UNITS USED**

Intensities I and I_0 are in watt/m^2 and angle θ in degrees.

Q. 1. ***Two polaroids are used to study polarisation. One of them (the polariser) is kept fixed and the other (the analyser) is initially kept with its axis parallel to the polariser axis. The analyser is then rotated through angles of 45°, 90° and 180° in turn. How would the intensity of light coming out of the analyser be affected for these angles of rotation, as compared to the initial intensity and why?***

Sol. Let I_0 be the intensity when the axis of analyser is parallel to the axis of polariser. By the law of Malus,

$I = I_0\cos^2\theta$

(i) When θ = 45°, $I = I_0\cos^2 45° = \frac{I_0}{2}$

(ii) When θ = 90°, $I = I_0\cos^2 90° = 0$

(iii) When θ = 180°, $I = I_0\cos^2 180° = I_0$

Q. 2. ***Two polarising sheets have their polarising directions parallel so that the intensity of the transmitted light is maximum. Through what angle must the either sheet be turned if the intensity is to drop by one-half?***

Sol. Here $I = \frac{I_0}{2}$

Using Malus law, $I = I_0 \cos^2 \theta$

$\therefore \quad \frac{I_0}{2} = I_0 \cos^2 \theta \quad$ or $\quad \cos \theta = \pm \frac{1}{\sqrt{2}}$

Hence $\theta = \pm 45°, \pm 135°$

The same effect occurs no matter which sheet is rotated or in which direction it is rotated.

Q. 3. ***Two Polaroids are crossed to each other. If one of them is rotated through 60°, then what percentage of the incident unpolarised light will be transmitted by the polaroids?***

Sol. Let I_0 be intensity of incident unpolarised light. Then the intensity of light emerging from the first polaroids will be

$$I_1 = \frac{I_0}{2}$$

If θ is the angle between the transmission directions of the two polaroids, then the intensity of light emerging from second polaroids is

$$I_2 = I_1 \cos^2 \theta = \frac{I_0}{2} \cos^2 \theta$$

Initially the two polaroids are crossed to each other i.e., $\theta = 90°$

When polaroid is rotated through 60°, the angle between their polarising directions will become

$$\theta = 90° - 60° = 30°$$

$\therefore \quad I_2 = \frac{I_0}{2} \cos^2 30° = \frac{I_0}{2} \times \left(\frac{\sqrt{3}}{2}\right)^2$

$= \frac{3}{8} I_0 \quad$ or $\quad \frac{I_2}{I_0} = 0.375$

$\therefore$ Transmitted percentage

$= \frac{I_2}{I_0} \times 100 = 0.375 \times 100 = 37.5\ \%$

Q. 4. ***Two polaroids are placed 90° to each other. What happens when N – 1 more polaroid are inserted between two crossed polaroids (at 90° to each other). Their axes are equally spaced. How does the transmitted intensity behave for large N?***

Sol. Transmitted intensity through first polaroid is $\quad I_1 = I_0 \cos^2 \theta$

where I_0 is the original intensity. Similarly, the transmitted intensity through second polaroid will be

$$I_2 = I_1 \cos^2 \theta = I_0 \cos^4 \theta$$

If N polaroids are used, then

$$I_N = I_0 (\cos \theta)^{2N}$$

As the optic axes of the polaroids are equally inclined, so angle of rotation θ is same for each polariods. Thus

$$I_N = (\cos \theta)^{2N}$$

But angle between successive polaroids is

$$\theta = \frac{90°}{N} = \frac{\pi}{2N} \text{ radians}$$

$$\therefore \quad \left(\cos \frac{\pi}{2N}\right)^{2N} = \left(1 - \frac{\pi^2}{8\,N^2} + \ldots\right)^{2N} \simeq \left[1 - \frac{2\,N\,\pi^2}{8\,N^2} + \ldots\right]$$

which approaches 1 for large N. Hence fractional intensity,

$\frac{I_N}{I_0} = 1 \quad$ or $\quad I_N = I_0$

Q. 5. ***Unpolarised light of intensity 32 W m^{-2} passes through three polarisers such that the transmission axis of the last polariser is crossed with the first. If the intensity of the emerging light is 3 W m^{-2}, what is the angle between the transmission axes of the first two polarisers? At what angle will the transmitted intensity be maximum?***

Sol. Let P_1, P_2, P_3 be the three polarisers and θ be the angle between the transmission axes of P_1 and P_2. As P_1 and P_3 are crossed, the angle between P_2 and P_3 is $90° - \theta$.

Let I_0 be the intensity of the unpolarised light falling on P_1. Then the intensity of light emerging from P_1 will be

$$I_1 = \tfrac{1}{2} I_0$$

By Malus law, the intensity of light emerging from P_2 is

$$I_2 = I_1 \cos^2 \theta = \tfrac{1}{2} I_0 \cos^2 \theta.$$

The intensity of light emerging form P_3 is

$$I_3 = I_2 \cos^2 (90° - \theta) = \tfrac{1}{2} I_0 \cos^2 \theta \sin^2 \theta$$

$$= \frac{1}{8} I_0 \sin^2 2\theta$$

∴ $\sin^2 2\theta = \frac{8 I_3}{I_0} = \frac{8 \times 3}{32} = \frac{3}{4}$ or $\sin 2\theta = \sqrt{3}/2$

or $2\theta = 60°$ or $\theta = 30°$

As $I_3 = \frac{1}{8} I_0 \sin^2 2\theta$

∴ I_3 will be maximum when

$\sin^2 2\theta = 1$ (maximum) or $\sin 2\theta = 1 = \sin 90°$ or $\theta = 45°$

Q. 6. ***A polaroid examines two adjacent plane-polarised light beams A and B whose planes of polarisation are mutually at right angles. In one position of the polaroid, the beam B shows zero intensity. From this position a rotation of 30° shows the two beams of equal intensities. Find the intensity ratio I_A/I_B of the two beams.***

Sol. The planes of polarisation of light beams A and B are mutually at right angles. Initially, the beam B shown zero intensity. Therefore, $\theta = 90°$ for beam B and $\theta = 0°$ for beam A. When the polaroid is rotated through 30°, we have

$\theta = 60°$, for beam A and $\theta = 30°$ for beam B.

In this position, Intensity of emerging beam A = Intensity of emerging beam B

∴ $I_A \cos^2 30° = I_B \cos^2 60°$

or $\frac{I_A}{I_B} = \frac{\cos^2 60°}{\cos^2 30°} = \frac{(1/2)^2}{(\sqrt{3}/2)^2} = \frac{1}{3} = 1 : 3$

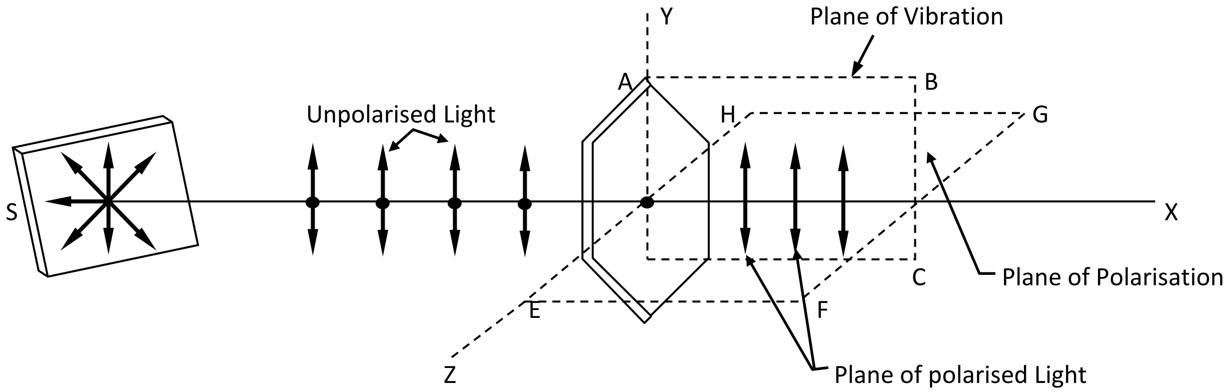
PLANES OF POLARISATION AND VIBRATION

Plane of vibration and plane of polarisation: When ordinary light is passed through a tourmaline crystal, the light is plane polarised and the vibrations of the electric field vector take place just in one direction perpendicular to the direction of propagation of light. The plane containing the direction of vibration and the direction of wave propagation is called the plane of vibration.

As shown in Fig. if light wave is propagating along X-axis and the electric field vector vibrates parallel to Y-axis, then ABCD or XY-plane is the plane of vibration.

The plane passing through the direction of wave propagating and perpendicular to the plane of vibration is called the plane of polarisation. No vibrations occur in the plane of polarisation.

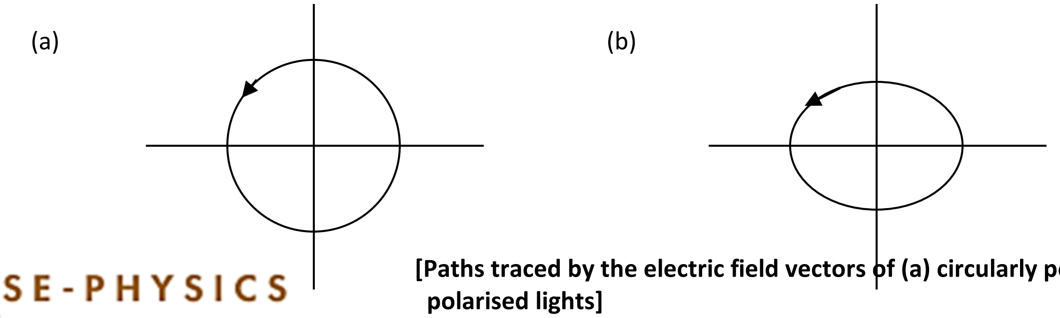
In Fig. EFGH or XZ-plane is the plane of polarisation.



[Plane of vibration and plane of polarisation]

CIRCULARLY AND ELLIPTICALLY POLARISED LIGHTS

Circulatory polarised light: If the tip of the electric field vector of a light wave traces a circle, the light is said to be circulatory polarised. It can be regarded as the combination of two plane polarised vibrations of equal amplitudes in two mutually perpendicular directions with a phase difference of $\pi/2$.



[Paths traced by the electric field vectors of (a) circularly polarised and (b) elliptically polarised lights]

Elliptically polarised light: If the tip of the electric field vector of a light wave traces an ellipse, the light is said to be elliptically polarised. It can be regarded as the combination of two plane polarised vibrations of unequal amplitudes in the mutually perpendicular directions with a phase difference of $\pi/2$.

METHODS OF PRODUCING PLANE POLARISED LIGHT

Methods of producing plane polarised light: Ordinary light can be polarised by using any of the following phenomena:

1. Reflection
2. Scattering
3. Double refraction
4. Selective absorption

POLARISATION BY REFLECTION: BREWSTER LAW

Polarisation by reflection: In 1808, the French physicist Malus discovered that when ordinary light is incident on the surface of a transparent medium, the reflected light is partially plane polarised. The extent of polarisation depends on the angle of incidence. For a particular angle of incidence, the reflected light is found to be completely polarised with its vibrations perpendicular to the plane of incidence.

The angle of incidence at which a beam of unpolarised light falling on the transparent surface is reflected as a beam of completely plane polarised light is called polarising or Brewster angle. It is denoted by i_p.

The British physicist David Brewster found that at the polarising angle, the reflected and transmitted rays are perpendicular to each other, as shown in Fig. Suppose i_p is the polarising angle of incidence and r_p, the corresponding angle of refraction. Then

$$i_p + r_p = 90^\circ$$

or $$r_p = 90^\circ - i_p$$

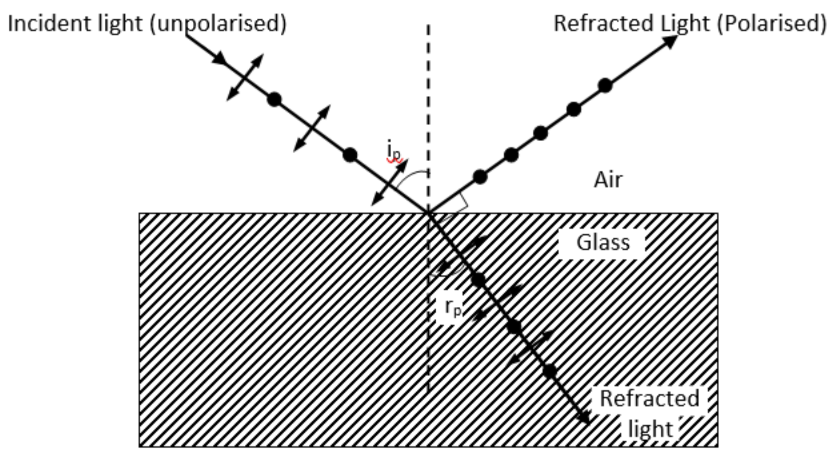
From snell's law, the refractive index of the transparent medium is

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

or $$\mu = \tan i_p$$

This relation is known as Brewster law. The law states that the tangent of the polarising angle of incidence of a transparent medium is equal to its refractive index.

The values of Brewster angle depends on the nature of the transparent refracting medium and the wavelength of light used.



[Polarisation of light reflected from a transparent medium at the Brewster angle]

Explanation: As shown in Fig. the incident unpolarised light has both types of vibrations, one perpendicular (dots) and other parallel to the plane of incidence. At the polarising angle of incidence (i_p), the reflected and refracted rays are perpendicular to each other. The electrons oscillating in the transparent medium produce the reflected wave. These vibrations move in two directions transverse to the refracted wave. As the arrows are parallel to the direction of reflected wave, they cannot send energy along the direction of reflected light. Hence the reflected light consists of vibrations perpendicular to the plane of incidence (dots) only i.e., the reflected light is plane polarised.

Examples based on Brewster Law

◆ **Formula Used**

1. Brewster law, $\mu = \tan i_p$
2. $i_p + r_p = 90^\circ$
3. $^2\mu_3 = \frac{^1\mu_2}{^1\mu_3}$

◆ UNITS USED

Angle i_p and r_p and in degrees, refractive index μ has no units.

Q. 1. ***Unpolarized light is incident on a plane glass. What should be the angle of incidence so that the reflected rays are perpendicular to each other?***

Sol. Here $i + r = 90^\circ$. Therefore,

$\tan i_p = \mu = 1.5$ [For glass, $\mu = 1.5$]

or $i_p = 56.3^\circ$

Q. 2. ***Yellow light is incident on the smooth surface of a block of dense flint glass for which the refractive index is 1.6640. Find the polarising angle. Also find the angle of refraction.***

Sol. Here $\mu = 1.6640$

By Brewster law, $\tan i_p = \mu$ $\therefore \tan i_p = 1.6640$

Hence $i_p = \tan^{-1}(1.6640) = 59.0^\circ$

If r is the angle of refraction, then $i_p + r = 90^\circ$

$\therefore$ $r = 90^\circ - i_p = 90^\circ - 59^\circ = 31^\circ$

Q. 3. ***A ray of light strikes a glass plate at an angle of 60°. If the reflected and refracted rays are perpendicular to each other, find the refractive index of glass.***

Sol. Reflected and refracted rays are mutually perpendicular only when the angle of incidence is equal to polarising angle, have

$i_p = 60^\circ$

$\therefore$ Refractive index, $\mu = \tan i_p = \tan 60^\circ = \sqrt{3} = 1.732$

Q. 4. ***At what angle of incidence will the light reflected from water (μ = 1.3) be completely polarised? Does this angle depend on the wavelength of light?***

Sol. Here $\mu = 1.3$, $i_p = ?$

As $\tan i_p = \mu = 1.3$ $\therefore$ $i_p = \tan^{-1} 1.3 = 53^\circ$

Yes, this angle depends on the wavelength of light used.

Q. 5. ***For a given medium, the polarising angle is 60°. What will be the refractive index and the critical angle for this medium?***

Sol. Here $i_p = 60^\circ$

$\therefore$ $\mu = \tan i_p = \tan 60^\circ = \sqrt{3}$

$\sin i_c = \frac{1}{\mu} = \frac{1}{\sqrt{3}} = 0.5774$

$\therefore$ $i_c = \sin^{-1}(0.5774) = 35^\circ\ 16'$

Q. 6. ***The velocity of light in air is 3 × 10⁸ ms⁻¹ and that in water is 2.2 × 10⁸ ms⁻¹. Find the polarising angle of incidence.***

Sol. The refractive index of water is given by

$$\mu = \frac{\text{Speed of light in air}}{\text{Speed of light in water}} = \frac{3 \times 10^8}{2.2 \times 10^8} = 1.3636$$

Using Brewster law, $\tan i_p = \mu = 1.3636$

$\therefore$ $i_p = \tan^{-1}(1.3636) = 53.74^\circ$

Q. 7. ***The refractive index of water is 4/3 and that of glass 3/2. A beam of light travelling in water enters glass. For what angle of incidence, the reflected light will be completely plane-polarised? (tan 48°22′ = 1.125)***

Sol. Here ${}^a\mu_w = \frac{4}{3}$ and ${}^a\mu_g = \frac{3}{2}$

$\therefore$ ${}^w\mu_g = \frac{{}^a\mu_g}{{}^a\mu_w} = \frac{3/2}{4/3} = \frac{9}{8} = 1.125$

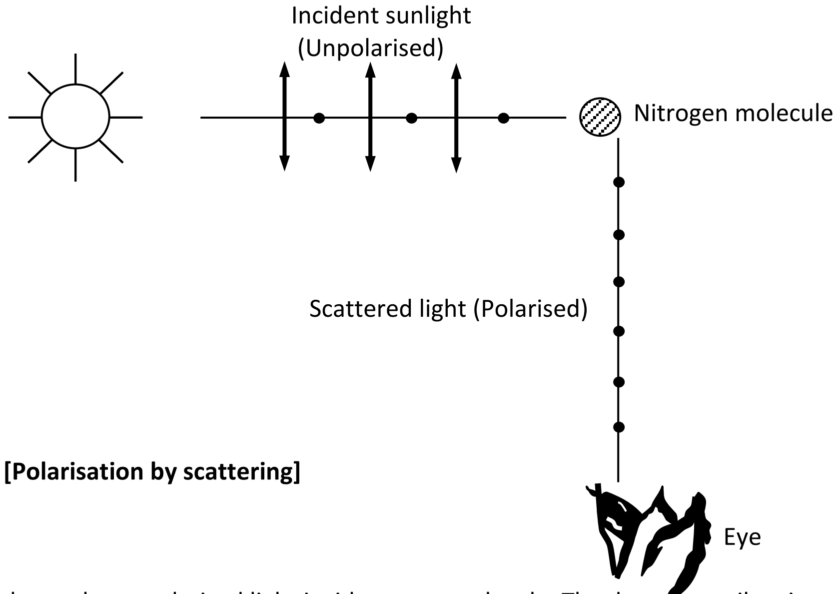
For a beam of light travelling from water to glass,

$\tan i_p = {}^w\mu_g = 1.125$

$i_p = \tan^{-1}(1.125) = 48^\circ\ 22'$

POLARISATION BY SCATTERING

Polarisation by scattering: If we look at the blue portion of the sky through a polaroid and rotate the polaroid, the transmitted light shows rise and fall of intensity. This shows that the light from the blue portion of the sky is plane polarised. This is because sunlight gets scattered (i.e., its direction is changed) when it encounters the molecules of the earth's atmosphere. The scattered light seen in a direction perpendicular to the direction of incidence is found to be plane polarised.



[Polarisation by scattering]

Explanation: Fig. shows the unpolarised light incident on a molecule. The dots show vibrations perpendicular to the plane of paper and double arrows show vibrations in the plane of paper. The electrons in the molecule begin to vibrate in both of these directions. The electrons vibrating parallel to the double arrows cannot send energy towards an observer looking at 90° to the direction of the sun because their acceleration has no transverse component. The light scattered by the molecules in these directions has only dots. It is polarised perpendicular to the plane of paper. This explains the polarisation of light scattered from the sky.

FOR YOUR KNOWLEDGE...

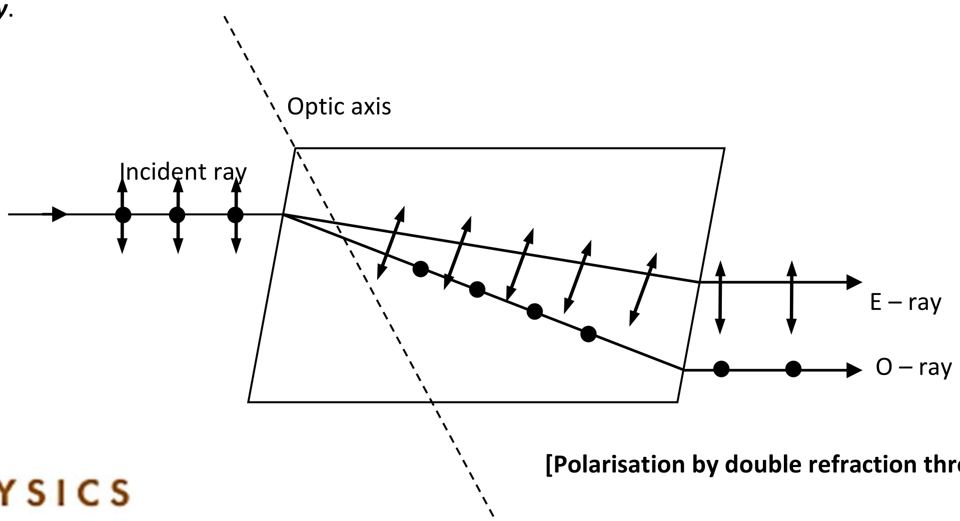
- In the nineteen twenties, C.V. Raman and his collaborators in Calcutta intensively investigated the scattering of light by molecules. Raman was awarded the Nobel Prize for Physics in 1930 for this work.
- Human eyes cannot distinguish between an unpolarised light and a polarised light. But the eyes of a bee can detect the differences. The bees can, not only, distinguish unpolarised light from polarised light but can also determine the directions of polarisation.

POLARISATION BY DOUBLE REFRACTION: NICOL PRISM

Polarisation by double refraction: When an unpolarised ray passes through certain crystals like quartz or calcite, it splits up into two rays, as shown in Fig. This phenomenon is called ***double refraction*** or ***birefringence***.

1. The one ray which obeys the ordinary laws of refraction and has vibrations perpendicular to the plane of incidence (dots) is called ***O-ray*** or ***ordinary ray***.

2. The other ray which does not obey the laws of refraction and has vibrations parallel to the plane of incidence is called ***E-ray*** or ***extra-ordinary ray***.



[Polarisation by double refraction through a calcite crystal]

Thus, both the refracted rays are plane polarised in mutually perpendicular directions. To install the phenomenon of double refraction, make an ink dot on while paper and look it through a calcite crystal. Two images are seen. If the crystal is rotated about the direction of incident light, it is seen that the image due to O-ray remains stationary while the image due to the E-ray rotates in the directions of rotation of the crystal.

Optic axis: It is a particular direction in the crystal along which both the O and E-rays have equal value of refractive index of the crystal and travel with some velocity and hence there is no double refraction in this direction. Along this direction, the images due to O-and E-rays coincide.

Principal section: Any plane which contains the optic axis and is perpendicular to the two opposite refracting faces of a crystal is called a principal section of the crystal.

44. Explain the principle, construction and working of a nicol prism.

Nicol Prism: It is an optical device based on the phenomenon of double refraction which is used for producing and analysing plane polarised light. It was invented by William Nicol in 1828.

Principle: When a thin film of Canada balsam is placed between two calcite pieces, the O-rays of the unpolarised incident light get eliminated through the phenomenon of total internal reflection while the E-rays are transmitted unaffected and emerge as a beam of plane polarised light.

Construction: The Nicol prism consists of two calcite crystal cut at 68° angle with its principal axis joined by a glue called Canada balsam. Canada balsam has a refractive index of 1.55, while the refractive index of calcite for the O-rays is 1.658 and that for E-rays is 1.486. Thus, Canada balsam acts as a rarer medium for O-rays and a denser medium for E-rays.

Working: Fig. shows the principal section ACGE of a Nicol prism. The diagonal AG represents the Canada balsam layer. When a ray of unpolarised light passes from a portion of the calcite crystal into the layer of Canada balsam, it passes from a denser to a rarer medium. When the angle of incidence is greater than the critical angle ($\approx 69°$), the ray is totally reflected and absorbed by a blackened surface. The E-ray is not affected because it is travelling from rarer medium (calcite) to denser medium (Canada balsam). It gets transmitted through the Nicol prism. Hence a ray of unpolarised light on passing through the Nicol prism becomes plane polarised containing vibration parallel to the principle section.

Canada balsam

A B

90°

Unpolarised Light Extraordinary ray

Polarised light

68°

C G

[Nicol prism as a polariser]

Ordinary ray

FOR YOUR KNOWLEDGE...

- **Quarter-wave half-wave plates:** For a double refracting crystal, the refractive indices for O-ray and E-ray are different and are denoted by μ_0 and $\mu_{e'}$ respectively. When these rays pass introduced between the two rays is

$$p = t(\mu_0 \sim \mu_e)$$

A plate which introduces a path differences of $\lambda/4$ between O-rays and E-rays is called a quarter wave plate. The thickness of a quarter wave plate is

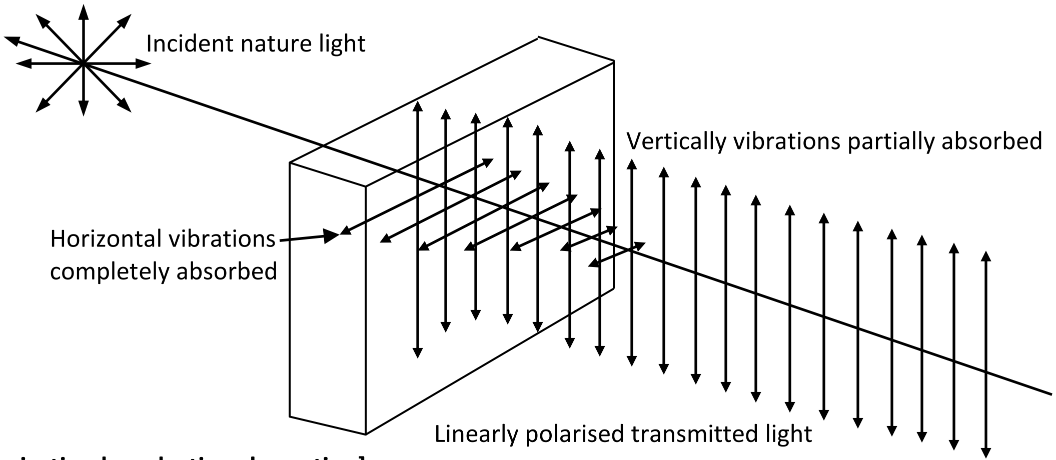
$$T_{1/4} = \frac{\lambda}{4(\mu_0 \sim \mu_e)}$$

A plate that introduces a path difference of $\lambda/2$ (or a phase difference of π) between O-rays and E-rays is called a half-wave plate. The thickness of a half-wave plate is

$$T_{1/2} = \frac{\lambda}{2(\mu_0 \sim \mu_e)}$$

POLARISATION BE SELECTIVE ABSORPTION: DICHROISM

Polarisation by selective absorption or dichroism: Certain doubly refracting crystals have the property of absorbing one of the doubly refracted beams to a greater extent than the other. The crystals showing this property are said to be dichroic and the phenomenon is known as dichroism. Tourmaline is a naturally occurring crystal which shows this phenomenon of selective absorption. As shown in Fig. when unpolarised light is passed through a tourmaline crystal of sufficient thickness, the O-ray is completely absorbed while. the E-ray is almost completely transmitted. So, the emergent light is plane polarised.

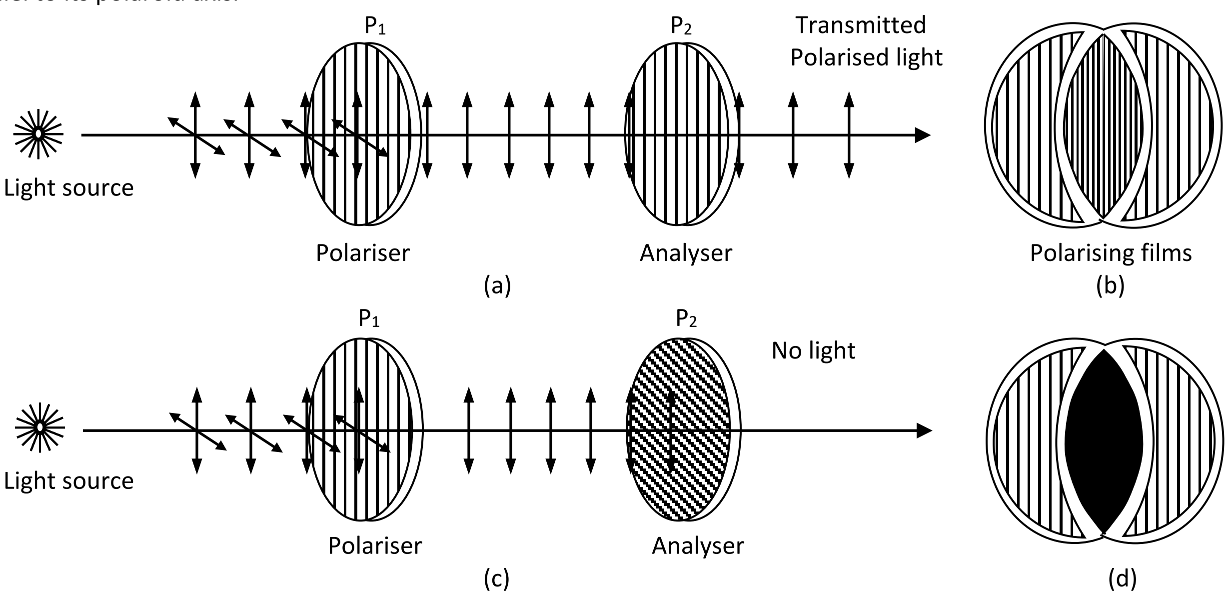


[Polarisation by selective absorption]

POLAROIDS

Polaroids: Polaroids are thin commercial sheets which make use of the property of selective absorption to produce an intense beam of plane polarised light.

In 1932, an American scientist Edwin Land developed a polariser in the form of large sheets. When a paste of quinine iodosulphate made in nitrocellulose is squeezed out through a fine slit, the needle-shaped crystals of quinine iodosulphate align themselves parallel to their optic axis. These crystals are highly dichroic. They absorb one of the doubly refracted beams completely. The thin polarising sheet so obtained is enclosed between two thin glass plates for mechanical support and we get a polaroid. Each polaroid has a characteristic direction called polaroid axis (shown by parallel lines). A polaroid transmits only those vibrations which are parallel to its polaroid axis.



[Polaroid films. When the film sheets are oriented with the same polarisation direction, the transmitted light is polarised (a and b). When one of the sheets is rotated 90° (crossed polaroids) no light is transmitted (c and d).]

As shown in Fig., when a beam of unpolarised light falls on a polaroid P_1, it transmits only those vibrations which are parallel to its polaroid axis. It absorbs the vibrations which are parallel to its polaroid axis. It absorbs the vibrations in the perpendicular direction. Thus, the transmitted light is plane-polarised. This can be examined by using a second polaroid P_2. When the polaroid axes of the two polaroids are parallel to each other [Fig. (a) and (b)], the plane-polarised light transmitted by P_1 is also transmitted by P_2, when the second polaroid is rotated through 90° (cross polaroids), no light is transmitted by P_2 [Fig. (c) and (d)].

FOR YOUR KNOWLEDGE...

- Improved polaroid films have been developed by using polymer materials. If a film of polyvinyl alcohol (PVA) is stretched to 3 to 8 times its original length, its molecule get oriented in the direction of stress and the film becomes doubly refracting. When the stretched film of PVA is impregnated with iodine, it becomes dichroic. The polaroid film so obtained is called ***H-polaroid***.

  If instead of impregnating with iodine, the stretched film is heated in the presence of a strong dehydrating agent, it becomes strongly dichroic dehydrating agent, it becomes strongly dichroic and very stable. This polaroid is called ***K-polaroid***.

USES OF POLAROIDS

Uses of polaroids: Polaroids have several uses in daily life:

1. In sunglasses and camera filters: Sunglasses and camera filters are made of polarising sheets to reduce the glare of light produced by reflection from shiny surface such as water surface.

2. In wind screens: The wind screens and car head lights of motor cars are fitted with polaroid films with their axes inclined at 45° to the horizontal. When two cars approach each other from opposite directions, the transmission planes of their wind screens will be perpendicular to each other, so the glare of their head lights is completely eliminated. Each driver sees the road by the light sent by his own car.

3. In window panes of aeroplanes: One of the polaroids is fixed while the other can be rotated to control the amount of light coming in.

4. In photoelasticity: Glass and some plastic materials exhibit double refraction only when stressed. If polarised light is passed through them and then analysed, the bright coloured lines indicated the existence of strains. In engineering work, plastic models of structure are constructed and weaknesses are examined in this way.

5. In Three-D movies: Three – D motion pictures are projected on screen by two projectors, each forming a slightly different image. One image is for one eye and other for the second eye so that the brain interprets this difference as depth or third dimensions. Lights from each projector are plane polarised, but in mutually perpendicular directions. The two 3-D glasses are really polarising glasses with their directions of polarisation perpendicular to each other. So one eye sees one image and other sees a slightly different image.

6. In liquid crystal displays (LCDs). An important application of polarisation is in liquid crystal displays or LCDs, used in many watches, calculators and portable computers (lap tops). Liquid crystals have long molecules whose directions can be controlled by applying electric fields. This fact is used in rotating the plane of polarisation of light produced by a polariser so that its polarisation is perpendicular to the axis of an analyser which cuts it out. These dark regions can be controlled with applied voltages and used to form letters and numbers.

DETECTION OF PLANE POLARISED LIGHT BY POLAROIDS

The given light is passed through a polaroid and the polaroid is rotated about the direction of incident light. The intensity of the emergent light is observed.

1. If on rotating the polaroid through one complete rotation, there is no change in the intensity of emergent light, then the given light is unpolarised.

2. If the intensity of emergent light shows alternate rise and fall and becomes light shows alternate rise and fall and becomes twice maximum and twice zero in one complete rotation of the polaroid, then the given light is plane-polarised or linearly polarised.

3. If the intensity of emergent light becomes twice maximum and twice minimum (and not zero) in one complete rotation of the polaroid, then the given light is partially polarised.

DOPPLER EFFECT OF LIGHT*

When a source of sound travels towards an observer, the apparent frequency is higher than the frequency actually emitted by the source. When the source moves away, the apparent frequency is lower than the actual frequency. Doppler effect is a basic property of all waves and so occurs in case of light also.

Whenever there is a relative motion between source of light and observer, the frequency of light received by the observer is different from the frequency actually emitted by the source. This phenomenon of the apparent change in the frequency of light is called Doppler effect for light.

Expression for the apparent frequency of light: Suppose a source of light emits waves of frequency ν and wavelength λ. If c is the speed of light, then

$$\lambda = \frac{c}{\nu}$$

Suppose an observer moves towards the sources with velocity υ. In one second, the source and observer come closer by a distance υ.

∴ Apparent frequency = No. of light waves emitted per second by the source + No. of light waves contained in distance υ

or $$\nu' = \nu + \frac{\upsilon}{\lambda} = \nu + \frac{\upsilon}{c/\nu} = \nu + \nu \cdot \frac{\upsilon}{c}$$

or $$\nu' = \nu\left(1 + \frac{\upsilon}{c}\right) \quad \text{... (1)}$$

Clearly, ν' > ν i.e., the apparent frequency increases when source and observer approach each other.

When source and observer move away from each other, the apparent frequency can be obtained by replacing υ by – υ in the above equation. Then

$$\nu' = \nu\left(1 - \frac{\upsilon}{c}\right) \quad \text{... (2)}$$

Clearly, ν' < ν i.e., the apparent frequency decreases when source and observer move away from each other.

Blue shift and red shift: Equations (1) and (2) be combined together as

$$\nu' = \nu\left(1 \pm \frac{\upsilon}{c}\right)$$

or $\nu' = \nu = \pm \frac{\upsilon}{c} . \nu$

The frequency change $\Delta\nu = \nu' - \nu$ is called Doppler shift. Putting $\nu = \frac{c}{\lambda}$ and $\nu' = \frac{c}{\lambda'}$, we get

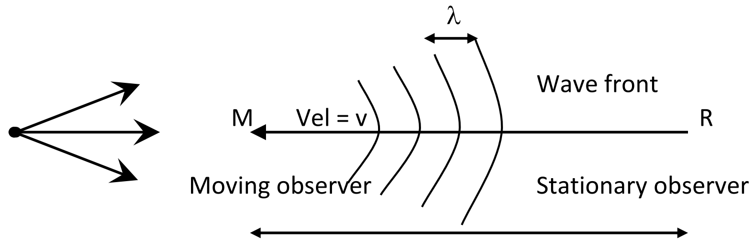
$$\frac{c}{\lambda'} - \frac{c}{\lambda} = \pm \frac{v}{c} . \frac{c}{\lambda}$$

or $\frac{\lambda - \lambda'}{\lambda'} = \pm \frac{v}{c}$

But $\frac{\lambda - \lambda'}{\lambda'} = \frac{\lambda - \lambda'}{\lambda}$

∴ $\frac{\lambda - \lambda'}{\lambda} = \pm \frac{v}{c}$

or $\lambda - \lambda' = \pm \frac{v}{c} \lambda$



(i) When source and observer approach each other, positive sign is taken. Then $\lambda - \lambda'$ is positive or $\lambda' < \lambda$, i.e., the wavelengths in the middle part of the visible spectrum shift towards the blue region. This is called **blue shift**.

(ii) When source and observer move away from each other, negative sign is taken. Then $\lambda - \lambda'$ is negative or $\lambda' > \lambda$, i.e., the wavelength in the middle part of the visible spectrum shift towards the red region. This is called **red shift**.

- **APPLICATIONS OF DOPPLER EFFECT:**

1. Light received from stars and galaxies shows a red shift which indicates that the universe is expanding.
2. By measuring Doppler shift in the e.m. wave reflected from an automobile, the speed of the automobile can be determined.
3. Doppler shift of light received from Saturn rings shows that the rings consist of a number of discontinuous satellites.
4. By measuring Doppler shift in the light received form eastern and western edges of the sun, the speed of rotation of the sun has been determined to be 2 km s^{-1} from east to west relative to the earth.

Examples based on Doppler Effect of Light

◆ **FORMULA USED**

1. $\frac{\Delta\nu}{\nu} = \frac{\nu' - \nu}{\nu} = \pm \frac{v}{c}$

2. $\frac{\Delta\lambda}{\lambda} = \frac{\lambda' - \lambda}{\lambda} = \mp \frac{v}{c}$

◆ **UNITS USED**

Frequencies ν and ν' are in hertz, velocities v and c in ms^{-1} and wavelength λ in metre.

◆ **CONSTANT USED**

Speed of light in free space = 3×10^8 ms^{-1}

Q. 1. ***What speed should a galaxy move with respect to us so that the sodium line at 589.0 nm is observed at 589.6 nm is observed at 589.6 nm?***

Sol. Here, $\lambda = 589.0$ nm, $\Delta\lambda = \lambda' - \lambda = 589.6 - 589.0 = 0.6$ nm

As $\Delta\lambda = -\frac{v}{c}\lambda$

∴ $v = -\frac{\Delta\lambda}{\lambda} . c$

$= -\frac{0.6}{589.0} \times 3 \times 10^8 = -3.09 \times 10^5\ ms^{-1}$

The negative sign shows that the galaxy is moving away from us.

Q. 2. ***The spectral line for a given element in light received from a distant star is shifted towards longer wavelength side by 0.025%. Calculate the velocity of star in the line of light.***

Sol. Given $\frac{\Delta\lambda}{\lambda} = 0.025\ \% = \frac{0.025}{100}$

Velocity of star in the line of sight is

$$v = -\frac{\Delta\lambda}{\lambda} \times c = \frac{0.025}{100} \times 3 \times 10^8 = -7.5 \times 10^4\ ms^{-1}$$

The negative shows that the star is receding.

Q. 3. ***The earth is moving towards a fixed start with a velocity of 30 km s^{-1}. An observer on the earth observes a shift of 0.58 Å in the wavelength of light coming from the star. Find the actual wavelength of light emitted by the star.***

Sol. Here $v = 30 \text{ km s}^{-1} = 30 \times 10^3 \text{ ms}^{-1}$, $\Delta\lambda = 0.58$ Å, $c = 3 \times 10^8 \text{ ms}^{-1}$

As $\Delta\lambda = \frac{v}{c} \cdot \lambda$

$\therefore$ $\lambda = \frac{c}{v} \cdot \Delta\lambda = \frac{3 \times 10^8}{30 \times 10^3} \times 0.58 \text{ Å} = 5800 \text{ Å}$

Q. 4. ***A radar wave has frequency of 8.1 × 1^9 Hz. The reflected wave from an aeroplane shows a frequency difference of 2.7 × 10^3 Hz on the higher side. Deduce the velocity of aeroplane in the line of sight.***

Sol. Here $v = 8.1 \times 10^9$ Hz, $\Delta v = 2.7 \times 10^3$ Hz

As $\Delta v = \frac{v}{c} \cdot v$

$\therefore$ $v = \frac{\Delta v}{v} \cdot c = \frac{2.7 \times 10^3}{8.1 \times 10^9} \times 3 \times 10^8 = 100 \text{ ms}^{-1}$

Since the velocity of the aeroplane determined by radar waves is double of its actual velocity of approach, therefore,

Actual velocity of the aeroplane = $50 \text{ ms}^{-1} = 180 \text{ km h}^{-1}$.

... **END.**