Chapter 10

WAVE THEORY OF LIGHT

Introduction:

The light is a form of energy which is emitted in the form of photons or in the form of waves. Due to light, we are able to see this beautiful world and realize the things. The nature of light to explain the phenomena such as reflection, refraction, diffraction, interference etc. were explained by various scientists with many theories, one of them was…

Newton's Corpuscular Theory:

Newton's corpuscular theory was based on postulates as follows:

1. Newton proposed that a source of light emits many minute, elastic, rigid and massless particles called corpuscles.
2. These particles travel through a transparent medium at very high speed in all direction along a straight line.
3. These corpuscles enter our eyes and produce the sensation of vision.
4. Due to different sizes of the corpuscles, they produce different colours.
5. These light particles are repelled by a reflecting surface and attracted by transparent materials.

Merits:

1. It explains the rectilinear propagation of light.
2. It could explain the reflection and refraction of light separately.

Drawbacks:

1. Newton's corpuscular theory fails to explain simultaneous phenomenon of partial reflection and refraction on the surface of transparent medium such as glass or water.
2. The corpuscular theory fails to explain optical phenomena such as interference, diffraction, polarization etc.
3. According to this theory, velocity of light is larger in the denser medium than in the rarer medium, experimentally it is proved wrong $(v_a < v_d)$.
4. As the particles are emitted from the source, mass of the source of light should decrease but experiment proved that mass of the source of light is constant.

Questions on above topic:

Q1. Explain in brief the Newton’s Corpuscular theory of light.

Q2. What are the draw backs of Newton’s Corpuscular theory of light.

Multiple Choice Questions:

1. Newton's corpuscular theory could explain correctly the phenomenon of :

   (a) interference of light (b) diffraction of light

   (c) rectilinear propagation of light (d)simultaneous reflection and refraction of light.

Maxwell's Electromagnetic Theory:

According to this theory light is electromagnetic waves. Experimentally it is observed that velocity of light is equal to velocity of electromagnetic waves. They travel even in vacuum.

Question on above topic:

Q. What was Maxwell's concept of light ?

Max Planks Quantum Theory:

According to this theory light is propagated in the form of packets of energy called quanta. Each quanta of light also called photon and it has energy

$$E = h\,\nu$$

Where, ν = Frequency of light

h = Plank's constant

Questions on above topic:

Q1. What is the photon model or quantum hypothesis of light?

Q2. Explain Max Plank's quantum theory of light.

Huygens' Wave Theory:

Postulates on which Huygens' wave theory are given as follows:

1. The source of light emits light in the form of waves.
2. Light waves are like sound wave, which are longitudinal in nature.
3. Light waves move with constant speed in a homogeneous medium.
4. Different colours of light are due to different wavelengths of light waves.
5. When light waves enter in our eyes we feel the sensation of vision.
6. Light waves travel through vacuum due to presence of a hypothetical medium called as luminiferous ether.

Merits:

1. Wave theory of light is helpful to explain phenomena such as reflection, refraction, interference and diffraction.
2. The phenomenon of Partial reflection and refraction of light can be satisfactorily explained using the wave theory of light.
3. As per the wave theory of light, velocity of light in optically denser medium is less than the velocity of light in a rarer medium, which is correct $(v_a > v_d)$.

Demerits:

1. Wave theory of light assumed the presence of hypothetical ether medium but experiment proved that there is no ether or drag.
2. Rectilinear propagation of light is not explained by this wave theory.
3. Wave theory of light could not explain phenomena such as Compton effect and polarization of light.
4. Wave theory of light could not explain bending of wave through an obstacle.
5. Wave theory of light assumed that light waves are longitudinal in nature but experiment proved that they are electromagnetic transverse waves.

Question on above topic:

Q. Give brief account of Huygens' wave theory of light. States its merits and demerits.

Multiple Choice Questions:

1. Huygens' wave theory of light could not explain:
   (a) reflection (b) refraction
   (c) interference (d) photoelectric effect

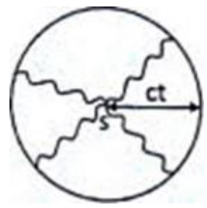
2. Huygens' original theory of light assumed that light propagates in the form of:
   (a) transverse mechanical waves. (b) longitudinal mechanical waves.
   (c) transverse electromagnetic waves. (d) minute elastic particles.

3. The phenomenon of diffraction and refraction indicates that light is having:
   (a) particle nature (b) wave nature
   (c) both particle and wave nature (d) neither particle nor wave nature

4. Two points, equidistant from a point source of light, are situated at diametrically opposite positions in an isotropic medium. The phase difference between the light waves passing through the two points is :
   (a) zero (b) π rad
   (c) $\pi/2$ rad (d) 2π rad

Definitions:

Wave surface: When a point source of light 'S' is situated in air then its waves travel In all possible directions. If 'c' is the velocity of light in air then each wave covers a distance 'ct' in time t and reaches the surface of a sphere.



Wavefront: "The locus of all points of the medium at which the waves reach simultaneously such that all points are in the same phase is called a wavefront".

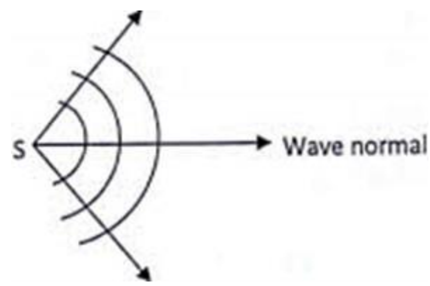
There are three type of wavefront:

I. Spherical wavefront
II. Plane wavefront
III. Cylindrical wavefront

Spherical wavefront:

A wavefront in the form of spherical surfaces is called spherical wavefront.

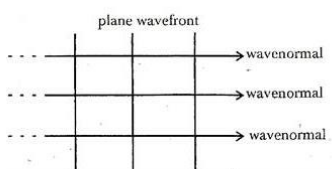
It is obtained from a point source of light up to a finite distance.



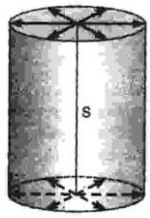
Plane Wavefront:

A wavefront in the form of plane surface is called plane wavefront.

It is obtained by keeping point source at a focus of a convex lens or at a large distance from the point source.



Cylindrical Wavefront:



It wavefront in the form of cylindrical surface is a cylindrical wavefront It is obtained from an extended light source.

Wave normal: A normal drawn on the surface of the wavefront at any point in the direction of propagation of light is called a wave normal.

The ray of light shown in a plane wavefront or spherical wavefront is a wave normal. Wavefront transfers light energy in the direction perpendicular to its surface and is represented by a wave normal.

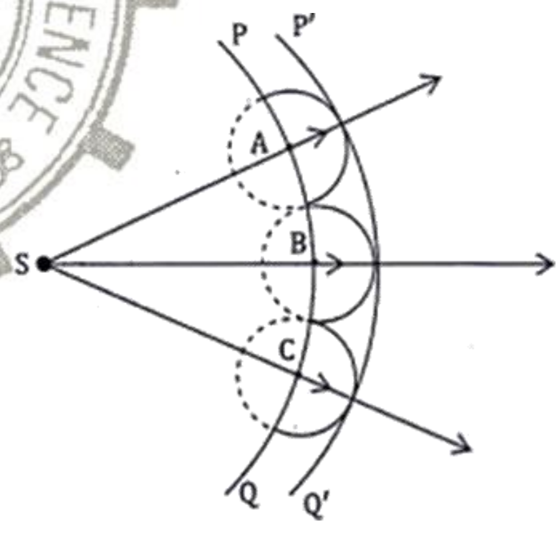
Huygens' Principle:

Huygens' principle is stated as follows,

- Each point on the wavefront acts as a secondary source of light emitting secondary waves in all possible direction.
- The secondary waves progressing forward direction only taken to be effective.
- The locus or tangential surface to all these secondary wave at any instant gives new wavefront at that given instant.

If nature and position of the wavefront at a given instant are known then by means of geometrical construction, it is possible to determine the nature and possible to determine the nature and position of the wavefront at a later instant. This is Huygens' construction.

Construction of Spherical Wavefront:



i. Let, PQ be a cross-section of a spherical wavefront emitted by a point source (S), at any instant. This can be called as primary wavefront.

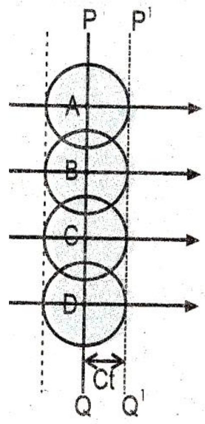
ii. Now consider points A, B, C on wavefront PQ. Thus, according to Huygens' Principle, they will act as secondary sources and emits secondary wavelets.

iii. If 'c' is the speed of light in the medium, then in time 't', each wave will describe a distance 'ct' in forward direction as the secondary waves moving in the backward direction do not exist.

iv. With points A, B, C as centres, circles can be drawn each of radius 'ct', This each circle will represent a secondary wavefront.

v. The common tangential surface P'Q' drawn to these secondary wavefronts represents the (new) position of the wavefront after time 't'.

Construction of Plane Wavefront:



I. Let, PO be a plane wavefront emitted by a point source (S) at any instant and at very large distance, this can be called as a primary wavefront.

II. Now consider points A, B, C on wavefront PQ, They act as secondary sources, and send out secondary wavelets as per Huygens' principle.

III. If 'c' is the speed of light in the medium, in time 't', each wave will describe a distance 'ct' in forward direction as the secondary waves moving in the backward direction do not exist.

IV. With A, B, C as centres, circles can be drawn each of radius 'ct', This each circle will represent a secondary wavefront.

V. The common tangential surface P'Q', drawn to these secondary wavefronts represents the new position for the plane wavefront after time 't'.

Questions on above topic:

Q1. State Huygens' principle and explain the Huygens' construction of a spherical wavefront.

Q2. Using Huygens' principle, explain the construction of a plane wavefront.

Multiple Choice Questions:

1. In an isotropic medium, the secondary wavelets centred on every point of a given wavefront are all

   (a) spherical (b) cylindrical
   (c) oval (d) of arbitrary shape

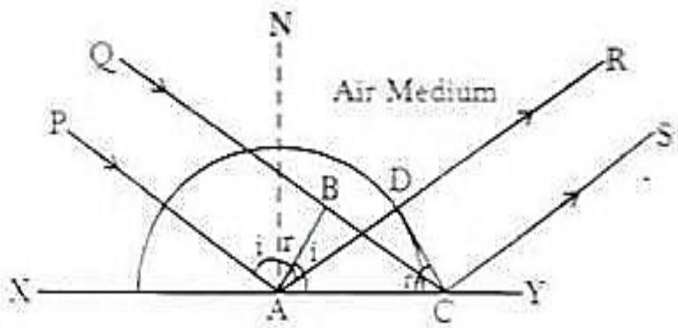
2. A point source of light is kept at the focus of a convex lens. The wavefront emerging from the lens is :

   (a) A plane wavefront (b) A diverging wavefront
   (c) A spherical wavefront (d) A cylindrical wavefront

3. As a plane wavefront propagates its radius of curvature:

   (a) decreases (b) increases
   (c) first increases and then decreases (d) becomes infinity

Reflection at a Plane Surface:



From figure,

XY = Plane refracting surface,

NA = Normal drawn to XY,

PA and QC = incident light rays,

∠PAN=∠BAC=∠i= angle of incidence

AR and CS = reflected light rays,

$\angle RAN = \angle DCA = \angle r =$ angle of reflection

AB = incident plane wavefront,

CD = reflected plane wavefront.

Explanation of reflection of light from reflecting surface :

1. Let XY is plane reflecting surface.
2. Consider AB is a plane wavefront bounded by rays PA and QB. Let AB is incident obliquely on surface XY, in air medium.
3. Wavefront first reaches to point A and it act as secondary source of light and will emit secondary waves in air.
4. Suppose that the incident wavefront travels from B to C in time t.

   $\therefore BC = c\,t$

   Where c = Velocity of light in air.
5. During time t, secondary waves from point A, will covers equal distance to BC. So, Where, radius of secondary wavefront will be equal to BC.
6. Taking A as a centre and radius BC draw a hemisphere which represent secondary wavelets.
7. Draw a tangent CD to hemisphere.
8. The point C and D are in the same phase as light has travelled for equal time to reach this point. Hence CD represents the reflected wavefront bounded by rays AR and CS.
9. The hemisphere has a radius AD.

$$\therefore AD = BC = ct$$

From the Figure

$$\angle PAN = \angle BAC = \angle i$$

$$\angle RAN = \angle DCA = \angle r$$

Also from figure

In Δ ABC and Δ ADC

$$\angle ABC = \angle ADC = 90^0$$

AC is common

BC = AD = ct

$$\therefore \Delta ABC \cong \Delta ADC$$

$$\therefore \angle BAC = \angle DCA$$

$$\angle i = \angle r$$

(i) Thus angle of incidence is equal to the angle of reflection.

(ii) The incident ray, reflected ray and the normal lies in the same plane.

(iii) The incident ray, the reflected ray lie on the opposite sides to that of normal.

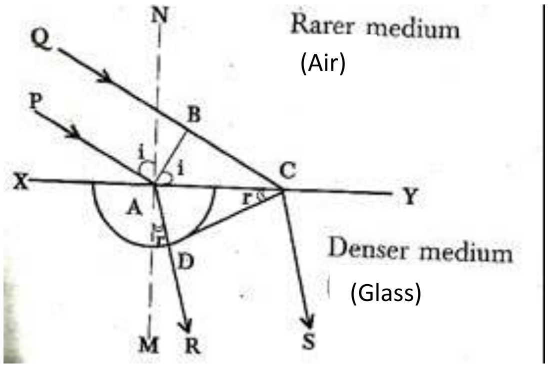
Hence law of reflection is proved by Huygens' wave theory.

Refraction of wavefront at Plane Surface:

From figure,

XY = Plane refracting surface,

NAM = Normal drawn to XY,



PA and QC = incident light ray,

$\angle PAN = \angle BAC = \angle i$= angle of incidence

AR and CS = refracted light ray,

$\angle MAD = \angle DCA = \angle r =$ angle of refraction

AB = incident plane wavafront,

CD = refracted plane wavefront.

Explanation of refraction of light from refracting surface :

1. Let XY be refracting surface separating rarer medium (air) and denser medium (glass)
2. Consider AB is a plane wavefront bounded by rays PA and QB. Let AB be incident obliquely on surface XY in air medium.
3. Wavefront first reaches to point A and acts as secondary source of light and will emit secondary waves in denser medium.
4. Suppose that the incident wavefront travels from B to C in time t.

   $\therefore$ BC $= c_1$t

   $c_1 =$ Velocity of light in rarer medium.
5. During time t, secondary waves from point A will covers distance equal to c_2t in denser medium. Where,c_2 = velocity of light in denser medium.
6. Taking A as a centre and radius c_2 t, draw a hemisphere in the denser medium which represent secondary wavelets.
7. Draw a tangent CD to hemisphere.
8. The point C and D are in the same phase. Hence CD represents the refracted wavefront bounded by rays AR and CS.
9. The hemisphere has a radius AD.

$\therefore AD = c_2 t$

To Prove law of refraction :

From the fig.

$\angle i + \angle NAB$=90^0 ……. (i)

$\angle NAB + \angle BAC$= 90^0 …….. (ii)

From eq$^{\mathrm{n}}$(i)and eq$^{\mathrm{n}}$ (ii), we get

$\angle NAB + \angle BAC = \angle i + \angle NAB$

$\angle BAC$=$\angle i$ …….(iii)

Now, in $\Delta ABC,$

$\sin i = \frac{BC}{AC}$ ……(iv)

Also,

$\angle r + \angle DAC = 90^0$ ……..(v)

And in ΔADC,

$\angle DAC + \angle DCA = 90^0$ ……..(vi)

From eq^n (iv) and eq^n(v), We get

$\angle DAC = \angle r$

In $\Delta ADC,$

$\sin r = \frac{AD}{AC}$ ………(vii)

Dividing eq^n (iv) and eq^n (vii), we get

$$\frac{\text{Sin i}}{\text{sin r}} = \frac{\text{BC}}{\text{AC}} \times \frac{\text{AC}}{\text{AD}}$$

$$\frac{BC}{AD} = \frac{C_1\, t}{C_2 t}$$

$$\therefore \frac{\text{Sin i}}{\text{sin r}} = \frac{C_1}{C_2}$$ ……..(viii)

By definition of refractive indices,

$${}^1\mu_2 = \frac{\mu_2}{\mu_1} = \frac{C_1}{C_2} = \frac{\textit{velocity of light in rarer medium}}{\textit{velocity of light in denser medium}}$$

${}^1\mu_2 =$ Refractive index of Denser medium w.r.t. rarer Medium.

Put in eq^n (viii), We get

$${}^1\mu_2 = \frac{\mu_2}{\mu_1} = \frac{\text{Sin i}}{\text{sin r}}$$

i.e.

$$\frac{\text{Sin i}}{\text{sin r}} = \frac{C_1}{C_2} = \frac{\mu_2}{\mu_1}$$ ……. (ix)

(i) Thus incident ray and refracted ray are on the opposite sides of the normal at the point of incidence and all three lie in same plane.

(ii) For given pair of media the ratio of the sine of the angle of incidence to sine of the angle of refraction is constant.

Hence law of refraction is proved by Huygens' wave theory.

To Show That $c_1 > c_2$:

From fig.

$\angle i > \angle r$;

sin i > sin r

$\frac{\sin i}{\sin r} > 1$

$\therefore \mu_2 > 1$

Refractive index of denser medium is always greater than 1.

$\therefore$ from equation (ix) it is clear that, $c_1 > c_2$

Thus, velocity of light in rarer medium is always greater than the velocity of light in denser medium.

Questions on above topics:

Q1. Explain the phenomenon of reflection on the basis of Huygens' wave theory of light.

OR

With a neat labelled diagram, explain reflection of light from a plane reflecting surface on the basis of wave theory of light.

Q2. Deduce the laws of refraction of light from Huygens' wave theory of light.

OR

On the basis of Huygens' wave theory of light, prove that the velocity of light in a rarer medium is greater than the velocity of light in a denser medium.

OR

Explain refraction of light on the basis of wave theory. Hence prove the laws of refraction.

Problems on above topics:

Some Useful Formulae from Class XI:

1. Absolute refractive index (n) of a medium

$$= \frac{\text{speed of light in vacuum or free space } (c)}{\text{speed of light in the medium } (v)}$$

2. Refractive index of medium 2 with respect to medium 1,

$${}_1n_2 = \frac{\text{speed of light in medium 1 } (v_1)}{\text{speed of light in medium 2 } (v_2)} = \frac{n_2}{n_1}$$

$${}_1n_2 = \frac{n_2}{n_1} = \frac{v_1}{v_2} = \frac{\lambda_1}{\lambda_2} \text{ (for the same frequency of light)}$$

3. ${}_1n_2 = \frac{\sin i}{\sin r}$ = constant for a given pair of mediums and given frequency of light

4. Wave number $\bar{v}$ (number of waves per unit length) $= \frac{1}{\lambda} = \frac{v}{c}$

1. The wavelengths of a certain light in air and in a medium are 4560 Å and 3648 Å, respectively. Compare the speed of light in air with its speed in the medium.

Solution: Let v_a and v_m be the speeds of light in air and in the medium respectively and let λ_a and λ_m be the wavelengths of light in air and in the medium respectively.

Let v be the frequency of light in air.

When light passes from one medium to another, its frequency remains unchanged.

$$\therefore \ v_a = v\lambda_a \text{ and } v_m = v\lambda_m$$

$$\therefore \ \frac{v_a}{v_m} = \frac{\lambda_a}{\lambda_m}$$

Data : $\lambda_a = 4560 \text{ Å} = 4560 \times 10^{-10}$ m,

$\lambda_m = 3648 \text{ Å} = 3648 \times 10^{-10}$ m

$$\therefore \ \frac{v_a}{v_m} = \frac{4560 \times 10^{-10}}{3648 \times 10^{-10}} = 1.25$$

$$\therefore \ v_a : v_m = \mathbf{1.25 : 1}$$

2. The refractive indices of water for red and violet colours are 1.325 and 1.334, respectively. Find the difference between the speeds of the rays of these two colours in water. ($c = 3 \times 10^8$ m/s)

Solution:

Data : $n_r = 1.325$, $n_v = 1.334$, $c = 3 \times 10^8$ m/s

$$n_r = \frac{c}{v_r} \text{ and } n_v = \frac{c}{v_v}$$

$$\therefore v_r = \frac{c}{n_r} \text{ and } v_v = \frac{c}{n_v}$$

Since $n_r < n_v$, $v_r > v_v$

$\therefore$ The speed difference,

$$v_r - v_v = c\left(\frac{1}{n_r} - \frac{1}{n_v}\right)$$

$$= (3 \times 10^8)\left(\frac{1}{1.325} - \frac{1}{1.334}\right)$$

$$= \frac{3 \times 10^8 \times 0.009}{1.325 \times 1.334} = \mathbf{1.528 \times 10^6 \text{ m/s}}$$

3. Red light of wavelength 6400 Å in air has a wavelength of 4000 Å in glass. If the wavelength of violet light in air is 4400 Å, what is its wavelength in glass? Assume that the glass has the same refractive index for red and violet colours.

Solution:

Data : $\lambda_{r(air)} = 6400$ Å, $\lambda_{r(glass)} = 4000$ Å, $\lambda_{v(air)} = 4400$ Å

Let n be the refractive index of glass for both red and violet colours.

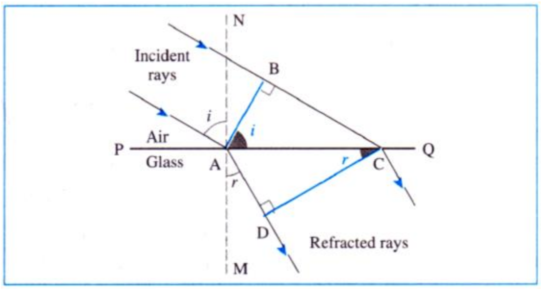
$$\therefore n = \frac{\lambda_{r(air)}}{\lambda_{r(glass)}} = \frac{\lambda_{v(air)}}{\lambda_{v(glass)}}$$

$$\therefore \lambda_{v(glass)} = \frac{\lambda_{r(glass)}}{\lambda_{r(air)}} \times \lambda_{v(air)}$$

$$= \frac{4000}{6400} \times 4400 = \mathbf{2750 \text{ Å}}$$

4. A parallel beam of monochromatic light is incident on a glass slab at an angle of incidence 60^0. Find the ratio of the width of the beam in glass to that in air if the refractive index of glass is 1.5.

Solution:



Data : $i = 60°$, ${}_an_g = 1.5$

By Snell's law, $${}_an_g = \frac{\sin i}{\sin r}$$

$$\therefore \sin r = \frac{\sin i}{{}_an_g}$$

$$\therefore \sin r = \frac{\sin 60°}{1.5} = \frac{0.8660}{1.5} = 0.5773$$

$$\therefore r = \sin^{-1}(0.5773) = 35°16'$$

From the figure, $\cos i = \frac{AB}{AC}$ and $\cos r = \frac{CD}{AC}$

$$\therefore \frac{\cos r}{\cos i} = \frac{CD}{AB}$$

$$\therefore \frac{CD}{AB} = \frac{\cos r}{\cos i} = \frac{\cos 35°16'}{\cos 60°} = \frac{0.8164}{0.5000} = 1.6328$$

$$\therefore \frac{\text{Width of the beam of light in glass}}{\text{Width of the beam of light in air}} = \mathbf{1.6328}$$

5. The width of a plane incident wavefront is found to be doubled in a denser medium if it makes an angle of 70° with the surface. Calculate the refractive index for the denser medium.

Solution: With reference to above problem,

Data : $i = 70°$, $\frac{CD}{AB} = 2$

$$\frac{\cos r}{\cos i} = \frac{CD}{AB} = 2$$

$$\therefore \cos r = 2 \cos 70° = 2 \times 0.3420 = 0.6840$$

$$\therefore r = \cos^{-1} 0.6840 = 46°51'$$

The refractive index of the denser medium relative to the rarer medium

$$= \frac{\sin i}{\sin r} = \frac{\sin 70°}{\sin 46°51'} = \frac{0.9397}{0.7296} = \mathbf{1.288}$$

Problem for Home Work:

1. The refractive indices of water and diamond are 1.33 and 2.42 respectively. Find the speed of light in water and diamond. Hence find the refractive index of diamond with respect to water.
2. The wavelength of blue light in air is 4500 ÅWhat is its frequency? If the refractive index of glass for blue light is 1.55, what will be the wavelength of blue light in glass?
3. A ray of light travelling through air, falls on the surface of a glass slab at an angle i. It is found that the angle between the reflected; and refracted ray is 90°. If the speed of light in glass is 2 $\times 10^8$ m/s find the angle of incidence.($c = 3 \times 10^8$ m/s)

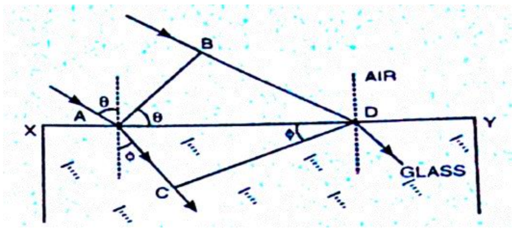
Multiple choice questions:

1. If the velocity of galaxy relative to earth is 1.2×10^6 m/s then % increase in wavelength of light from galaxy as compare to similar source on earth will be:

   (a) 0.3% (b) 0.4%

   (c) 0.5% (d) 0.6%

2. A wavefront AB moving in air is incident on a plane glass surface XY as given in figure. Its position CD after refraction through the glass slab is shown along with normals at A and D. The refractive index of glass with respect to air will be equal to:



(a) BD/AC (b) AB/CD

(c) BD/AD (d) AC/AD

3. When light is reflected from the surface of the mirror ,its speed and wavelength will :

(a) increase (b) decrease

(c) remain same (d) may increase or may decrease

4. A parallel beam of light travelling in glass is incident obliquely on water surface. After refraction, its width:

(a) decreases (b) increases

(e) remains the same (d) becomes zero

5. During the refraction of a green light from denser medium to rarer medium the property of light that always remains constant is its:

(a) speed (b) frequency

(c) wavelength (d) direction

6. The refractive index of glass and diamond with respect to air are 1.5 and 2.4 respectively. The refractive index of diamond with respect to glass is :

(a) 0.62 (b) 0.9

(c) 1.95 (d) 1.6

Polarization:

Light is electromagnetic wave in which electric and magnetic field vectors are sinusoidally, perpendicular to each other as well as perpendicular to direction of propagation of light wave.

Unpolarized light:

A light in, which the vibrations of the electric vectors are in all possible directions, which are perpendicular to the directions of propagation, is called as Unpolarized light.

Unpolarized light can be shown by a double arrow or large number of double arrows.

Fig: Representation of unpolarized light

Polarization of light:

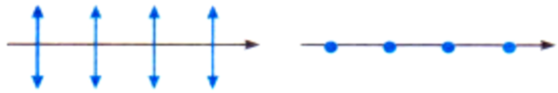
The phenomenon of restriction of the vibrations of light (electric vector) in a particular direction perpendicular to the direction of wave motion is called polarization of light.

Examples of polarizers are tourmaline crystal, Nicol prism, etc .

Plane-Polarized light:

When the vibrations of electric vectors are confined in one plane the light It is called plane polarized light.

This direction is perpendicular to the direction of propagation. Diagrammatically it is as shown below.

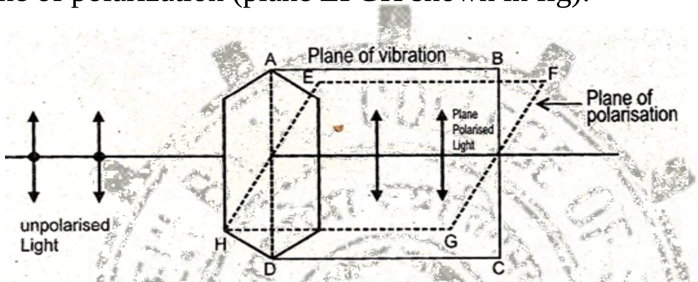


Plane of vibration:

The plane in which the vibrations of polarized light take place is called as plane of vibration (plane ABCD shown in fig).

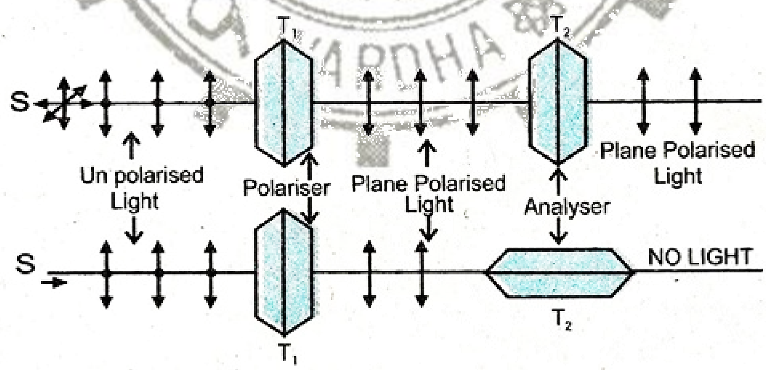
Plane of Polarization:

The plane perpendicular to the plane of vibration in which there are no vibrations of polarized light is called plane of polarization (plane EFGH shown in fig).



Experiment to demonstrate transverse nature of light.

1. A beam of light emitted by source 'S' is allowed to pass through tourmaline crystals. Consider two crystals T_1 and T_2 which are cut parallel to its crystallographic axis or optic axis, and kept with their axis parallel to each other. (as shown in figure)



2. Now rotate both the crystals together with their axis parallel to each other in all positions, then, it is found that no change in the intensity of light transmitted by crystal T_2 is observed.
3. When Crystal T_1 is kept fixed and T_2 is rotated then it is found that the intensity of light transmitted by T_2 decreases, finally intensity becomes zero when their axes are perpendicular to each other, which means no light is transmitted from T_2.
4. If crystal T_2 is rotated further again then the intensity of light transmitted from T_2 increases and finally it becomes maximum when they are again parallel.

Thus this experiment shows that light is not propagated as longitudinal waves and light waves are transverse in nature. The experiment also shows that light coming out of T_1 is polarized light.

Polaroid:

Polaroid's are large sheets made up of microscopic dichroic crystals which can produce a beam of polarized light.

Polaroid's are large-sized manufactured polarizing films capable of producing plane polarized beams of large cross-section.

Now a days, two types of polaroid's are produced H-polaroid and K-polaroid.

H-polaroid:

It is prepared by stretching a thin film of polyvinyl alcohol strained with iodine. It becomes highly dichroic. The sheet is mounted between two glass plates. This type of polaroid is called H-polaroid.

K-polaroid:

Land and Roger discovered that when a stretched film of polyvinyl alcohol is heated in the presence of HCl (i.e. a dehydrating catalyst), the film gets darkened and it exhibits strong dichroism. This type of polaroid is called K-polaroid.

Uses of Polaroid:

(1) In motor car head lights to remove headlight glare.

(2) In three dimensional movies cameras.

(3) To produce and analyze polarized light.

(4) It is used as filter in photographic cameras.

(5) In window of aero planes to control amount of light.

(6) In polarizing sunglasses (goggles) to protect the eyes from glare of sunlight.

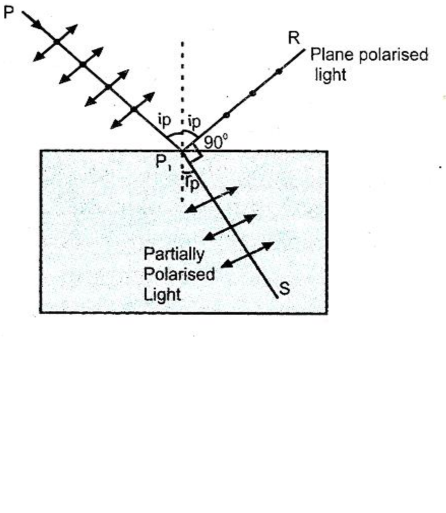
(7) They are used to improve colour contrast in old oil paintings.

(8) They are used in calculators, watches, monitors of laptops which have LCD screens.

Brewster's Law:

Statement:

It states that, the tangent of the polarizing angle is equal to the refractive index of the refracting medium at which partial reflection takes place.



Explanation:

1) When a beam of unpolarized monochromatic light is incident on a plane glass plate, part of the light is reflected while the rest is transmitted, the reflected light is partially polarized

2) At a certain angle of incidence, the reflected ray of light is completely plane polarized in the plane of incidence. This angle is known as polarizing angle.

3) These reflected and refracted rays are separated by 90^0 from each other. Then the tangent of the angle at which the complete polarization is obtained by reflection is numerically equal to refractive index of the reflecting medium.

Now, if 'i_p' is the polarizing angle and if 'μ' is the refractive index of the medium then from figure it is clear that

$$180^0 = i_p + 90^0 + r_p$$

Angle of refraction $r_p = 90^0 - i_p$

from snell's law, $$\mu = \frac{\sin i_p}{\sin\ r_p}$$

$$\therefore \quad \mu = \frac{\sin i_p}{\sin(90 - i_p)}$$

$$\therefore \quad \mu = \frac{\sin i_p}{\cos i_p}$$

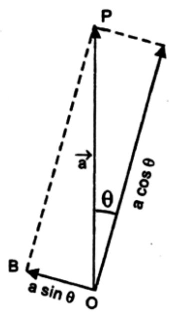
$$\therefore \quad \mu = \tan i_p$$

From Brewster's law, it follows that the polarizing angle is dependent on wavelength and is different for different colours. This law does not hold good for polished metallic surfaces.

Law of Malus:

When a beam of completely plane polarized light is incident on analyzer, the resultant intensity (I) of light transmitted from analyzer varies directly as the square of cosine of the angle (θ) between plane of transmission of analyzer and polarizer.

$$I \propto cos^2\ \theta$$



Questions on above topics:

Q1. What do you mean by polarization of light? How will you distinguish between polarized and unpolarized light?

Q2. Explain the transverse nature of light using tourmaline crystal.

Q3. Explain the term (i) Plane of vibration (ii) Plane of polarization.

Q4. State Brewster's law. Show that at the polarizing angle the reflected and the refracted rays are mutually perpendicular.

Q5. What are polaroid's? State some of the applications of polaroid.

Q6. What are polaroid's ? Explain in brief H-polaroid and K-polaroid.

Problems on above topics:

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

Solution: For i + r to be equal to π/2,

we should have

$\tan i_B = \mu = 1.5.$

This gives $i_B = 57°$. This is the Brewster's angle for air to glass interface.

2. The Wave length of a certain blue light in air and in water are 4800 Å and 3600 Å, respectively. Find the corresponding Brewster angle.

Solution:

Data : $\lambda_a = 4800$ Å, $\lambda_w = 3600$ Å

$$n = \frac{\lambda_a}{\lambda_w} \quad \text{and} \quad n = \tan i_p$$

$\tan i_p = 4800/3600 = 1.333$

$i_p = tan^{-1} 1.333$

$i_p = 53^0 4'$

Problems for home work:

1. A ray of light travelling through air falls on the surface of a glass slab at an angle i. It is found that the angle between the reflected and refracted ray is 90°.If the speed of light in glass is 2×10^8m/s, find the angle of incidence.($c = 3 \times 10^8$m/s)
2. If a glass plate of refractive index is 1.732 is to be used as a polarizer, what would be the (i) polarizing angle and (ii) angle of refraction?

Multiple choice questions:

1. Upolarized light of intensity I_0 falls on a Nicol prism. The light emerging from this Nicol Prism falls on another Nicol whose polarizing axis is inclined to that of first by an angle 30°. The light emerging from the second Nicol has the intensity :

   (a) $\frac{I_0}{\sqrt{2}}$ (b) $\frac{I_0}{2}$

   (c) $\frac{\sqrt{3}}{2} I_0$ (d) $\frac{3}{8} I_0$

2. Two nicols are crossed to each other. Now one of them is rotated through 60°. What percentage of incident light will pass through the system ?

   (a) 12% (b) 24%

   (c) 37.5% (d) 52%

3. An Unpolarized beam of light is incident on a group of four polarizing sheets which are arranged in such a way that the characteristic direction of each polarizing sheet makes an angle of 30° with the preceding sheet. What fraction of light is transmitted?

   (a) 27/54 (b) 27/81

   (c) 27/128 (d) 27/112

4. A ray of light is incident on the surface of a glass plate of μ = 1.5 at the polarizing angle. Calculate the angle of refraction of the ray :

(a) 12.5° (b) 24.6°
(e) 30.5° (d) 33.7°

5. A wave which cannot be polarized is :
(a) radio wave (b) ultrasonic wave
(c) infrared wave (d) X-ray

6. An electromagnetic wave is propagated along X direction. The XY plane is the plane of vibration. Then the plane of polarization is :
(a) YZ (b) XY
(c) XZ (d) YZ or XY or XZ

7. Light is incident at an angle i on a glass slab. If the reflected ray is completely polarized, then the angle of refraction is :
(a) 180 - i (b) 90 + i
(c) i (d) 90 – i

8. Light wave is incident on denser medium with angle of incidence equal to polarizing angle. If Deviation produced is 24°, then the angle of incidence is :
(a) 24° (b) 33°
(c) 57° (d) 81°

9. The angle of polarization for a transparent medium :
(a) does not depend on wavelength of light (b) increases as wavelength increases
(c) decreases as wavelength increases (d) changes irregularly with increase in wavelength.

Doppler Effect in Light:

The apparent change in in the frequency of an electromagnetic radiation as a result of relative motion between the source and observer is called the Doppler effect in light.

Doppler effect in light depends upon the relative velocity of source and observer irrespective of whether the source and observer are moving towards each other or moving away from each other or either of them stationary and the other is moving,

As light does not require medium for propagation, the velocity of light is same irrespective of movement of the source and observer.

The frequency of light measured by observer is given by,

$$\nu' = \nu \left(\frac{1 \pm \frac{v_r}{c}}{\sqrt{1 - \left(\frac{v_r}{c}\right)^2}} \right)$$

where, v_r = radial component of velocity of source relative to observer.

As, $v_r \ll c$, we have

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

Which leads to, $\frac{\Delta\nu}{\nu} = \frac{\Delta\lambda}{\lambda} = \frac{v_r}{c}$

Red and Blue Shift:

When the source and observer are moving away from each other then frequency of visible spectrum decreases and wavelength increases and spectrum is shifted towards red, is called as red shift.

When source and observer are approaching each other then frequency of visible spectrum increases and wavelength decreases and spectrum is shifted towards blue, is called as blue shift.

Applications of Doppler Effect:

(I). It is used for measurement of plasma temperature.

1. Plasma is fourth state of matter. In thermonuclear fusion experiments there are extremely hot gases or plasma. Here temperature is in the order of millions of degree Celsius.
2. At this high temperature some gas molecule are moving towards and some are moving away from observer with high speed.
3. According to Doppler effect wavelength λ of particular spectral line is apparently changed.
4. Due to the molecules which are moving away, wavelength of edge of spectral line will increased to λ_1 .
5. Due to the molecules which are coming towards the observer, wavelength of other edge of line will be decreased to λ_2.
6. The spectral line is broadened. Width of line can be measured using diffraction grating.
7. As λ and c are known, velocity v can be calculated. Using formula of kinetic theory of gases we can find temperature of plasma.

   Root mean square velocity = $\sqrt{\frac{3RT}{M}}$

   where,

   R – molar gas constant
   T – absolute temperature
   M – mass of one mole

(II) It is used to measure speed of rotation of sun.

1) To measure speed of rotation of sun is east and west edges of the sun are photographed.
2) In one case edge of sun approaches the earth and in other case opposite edge of sun recedes the earth.
3) Photograph contains lines of absorption spectra due to iron vaporized in sun and oxygen in earth's atmosphere.
4) When the two photographs are put together, oxygen lines coincide, the iron lines in the two photographs are displaced relative to each other.
5) When there is relative shifting between two photographs the lines will coincide.
6) By measuring the shift and using formula we can calculate the speed of rotation of sun.
7) Speed of rotation of sun is about 2 km/s.

Radar :

Radar is a system for locating distant object by means of reflected radio waves, usually of microwave frequencies. Radar is used for navigation and guidance of aircraft, ships etc.

Radar employs the Doppler effect to distinguish between stationary and moving targets. The change in frequency between transmitted and received waves in measured. If v is the velocity of the approaching target, then the change in
frequency is

$$\Delta v = \frac{2v}{c} v$$

(The factor of 2 arises due to reflection of waves. For a receding target $\Delta v = -\frac{2v}{c} v$

(The –ve sign indicates decrease in frequency)

Doppler's effect in light is symmetrical, but the same effect in sound is asymmetrical:

1. Sound waves require medium for propagation.
2. Speed of source and observer are measured relative to medium.
3. Therefore the frequency change depends on whether the source is moving or the observer is moving, even if the relative velocity is same.
4. So Doppler effect in sound is asymmetric.
5. Light does not require a medium for propagation, and speed of light is same for any observer whether the observer or source or both are moving.
6. It only depends on the relative velocity of the source and the observer, irrespective of which of the two is moving.
   Therefore Doppler's effect in light is symmetrical.

Questions on above topics:

Q1. Explain Doppler effect in light. Hence explain the red and blue shifts.
Q2. Give the uses of Doppler effect in light.
Q3. Doppler effect in light is said to be symmetric. Explain why?
Q4. Explain how Doppler effect can help to measure the speed and rotation of the sun.
Q5. Explain how Doppler effect is used to measure the temperature of plasma.

Multiple Chose Questions:

1. Doppler shift of light of wave length 6000 Å emitted from sun is 0.04 Å. If the radius of sun is 7×10^8m then time period of rotation of rotation of sun will be:
   (a) 30 days (b) 365 days
   (c) 24 hour (d) 25 days
2. A radar operates at wavelength 50 cm. If the beat frequency between the transmitted signal and the signal reflected from air craft ($\Delta\vartheta$)is 1 kHz, then velocity of aircraft will be:
   (a) 800 km/hr (b) 900 km/hr
   (c) 1000 km/hr (d) 1032m/hr
3. A spectral line of wavelength 0.59 mm is observed in the directions to the opposite edges of the solar disc along its equator. A difference in wavelength equal to ($\Delta\lambda$) 8 picometre is observed. Period of sun's revolution around its own axis will be about (Radius of sun = 6.95×10^8m).
   (a) 30 days (b) 35 days
   (c) 25 days (d) 365 days

4. The spectral line emitted by a star, known to have a wavelength of 6500 Å, when observed in the laboratory appears to have a wavelength 6525 Å. What is the speed of the star in the line of light relative to the earth for receding or approaching?

(a) 1.154×10^6 m/s receding (b) 1.154×10^4 m/s approaching

(c) 1.154×10^3 m/s receding (d) 1.154×10^2 m/s approaching.

5. The frequency of light wave emitted by a star is found to shift towards red end of the spectrum. With respect to an observer on the earth, the star is :

(a) stationary (p) moving away from earth

(c) moving towards the earth (d) moving in any direction

6. To measure the plasma temperature in thermonuclear fusion experiments, we use:

(a) Doppler effect (b) Photoelectric effect

(c) Compton effect (d) Interference of light

7. Doppler effect in light is :

(a) asymmetric (b) neither symmetric nor asymmetric

(c) symmetric (d) both symmetric and asymmetric