Wave Optics

Light Propagation

Light is a form of energy which generally gives the sensation of sight.

(1) **Different theories**

(2) **Optical phenomena explained (√) or not explained (×) by the different theories of light**

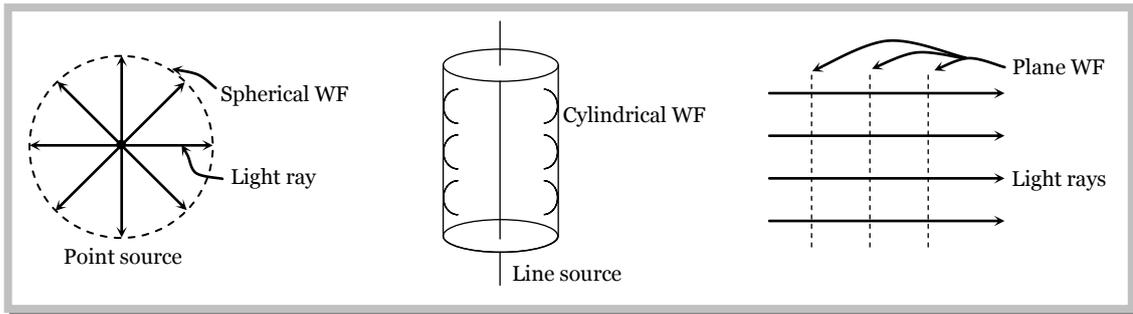(3) **Wave front**

(i) Suggested by Huygens

(ii) The locus of all particles in a medium, vibrating in the same phase is called Wave Front (WF)

(iii) The direction of propagation of light (ray of light) is perpendicular to the WF.

| Newtons corpuscular theory	Huygen's wave theory	Maxwell's EM wave theory	Einstein's quantum theory	de-Broglie's dual theory of light
(i) Based on Rectilinear propagation of light	(i) Light travels in a hypothetical medium ether (high elasticity very low density) as waves	(i) Light travels in the form of EM waves with speed in free space $c = \dfrac{1}{\sqrt{\mu_0 \varepsilon_0}}$	(i) Light is produced, absorbed and propagated as packets of energy called photons	(i) Light propagates both as particles as well as waves
(ii) Light propagates in the form of tiny particles called Corpuscles. Colour of light is due to different size of corpuscles	(ii) He proposed that light waves are of longitudinal nature. Later on it was found that they are transverse	(ii) EM waves consists of electric and magnetic field oscillation and they do not require material medium to travel	(ii) Energy associated with each photon $E = h\nu = \dfrac{hc}{\lambda}$ h = planks constant $= 6.6 \times 10^{-34}\ J\text{-sec}$ ν = frequency λ = wavelength	(ii) Wave nature of light dominates when light interacts with light. The particle nature of light dominates when the light interacts with matter (microscopic particles)

S. No.	Phenomena	Theory				
		Corpuscular	Wave	E.M. wave	Quantum	Dual
(i)	Rectilinear Propagation	√	√	√	√	√
(ii)	Reflection	√	√	√	√	√
(iii)	Refraction	√	√	√	√	√
(iv)	Dispersion	×	√	√	×	√
(v)	Interference	×	√	√	×	√
(vi)	Diffraction	×	√	√	×	√
(vii)	Polarisation	×	√	√	×	√
(viii)	Double refraction	×	√	√	×	√
(ix)	Doppler's effect	×	√	√	×	√
(x)	Photoelectric effect	×	×	×	√	√

(iv) **Types of wave front**

(v) Every point on the given wave front acts as a source of new disturbance called secondary wavelets. Which travel in all directions with the velocity of light in the medium.

A surface touching these secondary wavelets tangentially in the forward direction at any instant gives the new wave front at that instant. This is called secondary wave front
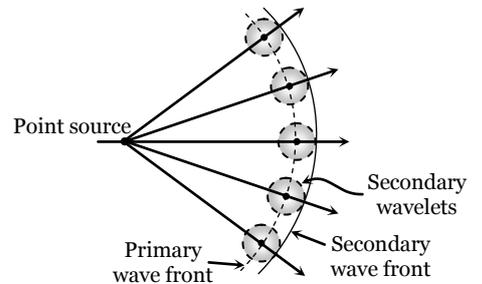
Note : ❑ Wave front always travels in the forward direction of the medium.

❑ Light rays is always normal to the wave front.
❑ The phase difference between various particles on the wave front is zero.

Principle of Super Position

When two or more than two waves superimpose over each other at a common particle of the medium then the resultant displacement (y) of the particle is equal to the vector sum of the displacements (y_1 and y_2) produced by individual waves. *i.e.* $\vec{y} = \vec{y}_1 + \vec{y}_2$

(1) **Graphical view :**

(i)

Waves are meeting at a point in same phase

(ii)



Waves are meeting at a point with out of phase

(2) **Phase / Phase difference / Path difference / Time difference**

(i) Phase : The argument of sine or cosine in the expression for displacement of a wave is defined as the phase. For displacement $y = a \sin \omega t$; term ωt = phase or instantaneous phase

(ii) Phase difference (ϕ) : The difference between the phases of two waves at a point is called phase difference *i.e.* if $y_1 = a_1 \sin \omega t$ and $y_2 = a_2 \sin(\omega t + \phi)$ so phase difference = ϕ

(iii) Path difference (Δ) : The difference in path length's of two waves meeting at a point is called path difference between the waves at that point. Also $\Delta = \dfrac{\lambda}{2\pi} \times \phi$

Division of wave front	Division of amplitude
The light source is narrow	Light sources is extended. Light wave partly reflected (50%) and partly transmitted (50%)
The wave front emitted by a narrow source is divided in two parts by reflection of refraction.	The amplitude of wave emitted by an extend source of light is divided in two parts by partial reflection and partial refraction.
The coherent sources obtained are imaginary *e.g.* Fresnel's biprism, Llyod's mirror Youngs' double slit *etc.*	The coherent sources obtained are real *e.g.* Newtons rings, Michelson's interferrometer colours in thin films
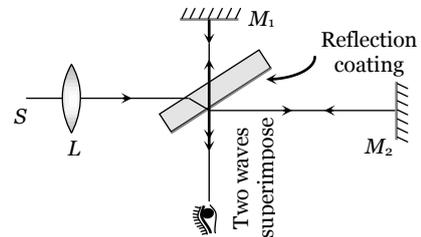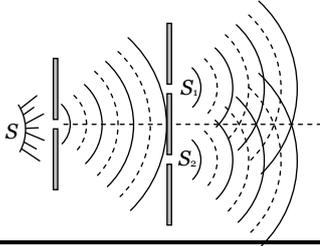
(iv) Time difference (*T.D.*) : Time difference between the waves meeting at a point is $T.D. = \dfrac{T}{2\pi} \times \phi$

(3) Resultant amplitude and intensity

If suppose we have two waves $y_1 = a_1 \sin \omega t$ and $y_2 = a_2 \sin(\omega t + \phi)$; where a_1, a_2 = Individual amplitudes, ϕ = Phase difference between the waves at an instant when they are meeting a point. I_1, I_2 = Intensities of individual waves

Resultant amplitude : After superimposition of the given waves resultant amplitude (or the amplitude of resultant wave) is given by $A = \sqrt{a_1^2 + a_2^2 + 2a_1 a_2 \cos \phi}$

For the interfering waves $y_1 = a_1 \sin \omega t$ and $y_2 = a_2 \cos \omega t$, Phase difference between them is 90°. So resultant amplitude $A = \sqrt{a_1^2 + a_2^2}$

Resultant intensity : As we know intensity $\propto$ (Amplitude)² $\Rightarrow I_1 = ka_1^2, I_2 = ka_2^2$ and $I = kA^2$ (k is a proportionality constant). Hence from the formula of resultant amplitude, we get the following formula of resultant intensity $I = I_1 + I_2 + 2\sqrt{I_1 I_2} \cos \phi$

Note : ❏ The term $2\sqrt{I_1 I_2} \cos \phi$ is called interference term. For incoherent interference this term is zero so resultant intensity $I = I_1 + I_2$

(4) Coherent sources

The sources of light which emits continuous light waves of the same wavelength, same frequency and in same phase or having a constant phase difference are called coherent sources.

Two coherent sources are produced from a single source of light by adopting any one of the following two methods

Note : ❏ Laser light is highly coherent and monochromatic.

❏ Two sources of light, whose frequencies are not same and phase difference between the waves emitted by them does not remain constant *w.r.t.* time are called non-coherent.

❏ The light emitted by two independent sources (candles, bulbs *etc.*) is non-coherent and interference phenomenon cannot be produced by such two sources.

❏ The average time interval in which a photon or a wave packet is emitted from an atom is defined as the **time of coherence**. It is $\tau_c = \dfrac{L}{c} = \dfrac{\text{Distance of coherence}}{\text{Velocity of light}}$, it's value is of the order of 10^{-10} *sec.*

Interference of Light

When two waves of exactly same frequency (coming from two coherent sources) travels in a medium, in the same direction simultaneously then due to their superposition, at some points intensity of light is maximum while at some other points intensity is minimum. This phenomenon is called Interference of light.

(1) **Types :** It is of following two types

Constructive interference	Destructive interference
(i) When the waves meets a point with same phase, constructive interference is obtained at that point (*i.e.* maximum light)	(i) When the wave meets a point with opposite phase, destructive interference is obtained at that point (*i.e.* minimum light)
(ii) Phase difference between the waves at the point of observation $\phi = 0^o$ or $2n\pi$	(ii) $\phi = 180^o$ or $(2n-1)\pi$; $n = 1, 2, ...$ or $(2n+1)\pi$; $n = 0,1,2.....$
(iii) Path difference between the waves at the point of observation $\Delta = n\lambda$ (*i.e.* even multiple of $\lambda/2$)	(iii) $\Delta = (2n-1)\dfrac{\lambda}{2}$ (*i.e.* odd multiple of $\lambda/2$)
(iv) Resultant amplitude at the point of observation will be maximum $a_1 = a_2 \Rightarrow A_{\min} = 0$ If $a_1 = a_2 = a_0 \Rightarrow A_{\max} = 2a_0$	(iv) Resultant amplitude at the point of observation will be minimum $A_{\min} = a_1 - a_2$ If $a_1 = a_2 \Rightarrow A_{\min} = 0$
(v) Resultant intensity at the point of observation will be maximum $I_{\max} = I_1 + I_2 + 2\sqrt{I_1 I_2}$ $I_{\max} = \left(\sqrt{I_1} + \sqrt{I_2}\right)^2$ If $I_1 = I_2 = I_0 \Rightarrow I_{\max} = 2I_0$	(v) Resultant intensity at the point of observation will be minimum $I_{\min} = I_1 + I_2 - 2\sqrt{I_1 I_2}$ $I_{\min} = \left(\sqrt{I_1} - \sqrt{I_2}\right)^2$ If $I_1 = I_2 = I_0 \Rightarrow I_{\min} = 0$

(2) **Resultant intensity due to two identical waves :**

For two coherent sources the resultant intensity is given by $I = I_1 + I_2 + 2\sqrt{I_1 I_2} \cos \phi$

For identical source $I_1 = I_2 = I_0 \Rightarrow I = I_0 + I_0 + 2\sqrt{I_0 I_0} \cos \phi = 4I_0 \cos^2 \dfrac{\phi}{2}$ $\qquad [1 + \cos\theta$

$= 2\cos^2 \dfrac{\theta}{2}]$

Note : ❏ In interference redistribution of energy takes place in the form of maxima and minima.

❏ Average intensity : $I_{av} = \dfrac{I_{\max} + I_{\min}}{2} = I_1 + I_2 = a_1^2 + a_2^2$

❏ Ratio of maximum and minimum intensities :

$$\frac{I_{max}}{I_{min}} = \left(\frac{\sqrt{I_1} + \sqrt{I_2}}{\sqrt{I_1} - \sqrt{I_2}}\right)^2 = \left(\frac{\sqrt{I_1/I_2} + 1}{\sqrt{I_1/I_2} - 1}\right)^2 = \left(\frac{a_1 + a_2}{a_1 - a_2}\right)^2 = \left(\frac{a_1/a_2 + 1}{a_1/a_2 - 1}\right)^2 \text{ also}$$

$$\sqrt{\frac{I_1}{I_2}} = \frac{a_1}{a_2} = \left(\frac{\sqrt{\frac{I_{max}}{I_{min}}} + 1}{\sqrt{\frac{I_{max}}{I_{min}}} - 1}\right)$$

❑ If two waves having equal intensity ($I_1 = I_2 = I_0$) meets at two locations P and Q with path difference Δ_1 and Δ_2 respectively then the ratio of resultant intensity at point P and Q will be

$$\frac{I_P}{I_Q} = \frac{\cos^2 \frac{\phi_1}{2}}{\cos^2 \frac{\phi_2}{2}} = \frac{\cos^2\left(\frac{\pi\Delta_1}{\lambda}\right)}{\cos^2\left(\frac{\pi\Delta_2}{\lambda}\right)}$$

Young's Double Slit Experiment (YDSE)

Monochromatic light (single wavelength) falls on two narrow slits S_1 and S_2 which are very close together acts as two coherent sources, when waves coming from two coherent sources (S_1, S_2) superimposes on each other, an interference pattern is obtained on the screen. In YDSE alternate bright and dark bands obtained on the screen. These bands are called Fringes.

d = Distance between slits
D = Distance between slits and screen
λ = Wavelength of monochromatic light emitted from source
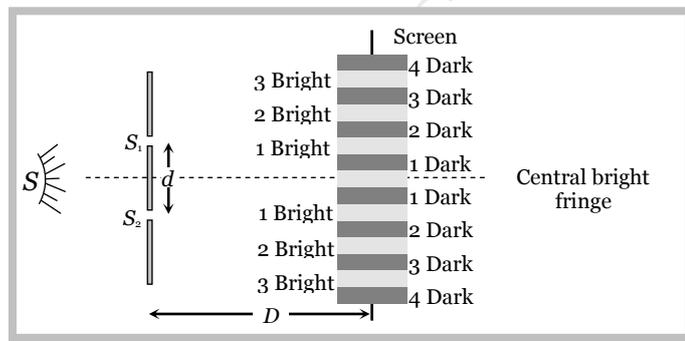
(1) Central fringe is always bright, because at central position $\phi = 0^o$ or $\Delta = 0$

(2) The fringe pattern obtained due to a slit is more bright than that due to a point.

(3) If the slit widths are unequal, the minima will not be complete dark. For very large width uniform illumination occurs.

(4) If one slit is illuminated with red light and the other slit is illuminated with blue light, no interference pattern is observed on the screen.

(5) If the two coherent sources consist of object and it's reflected image, the central fringe is dark instead of bright one.
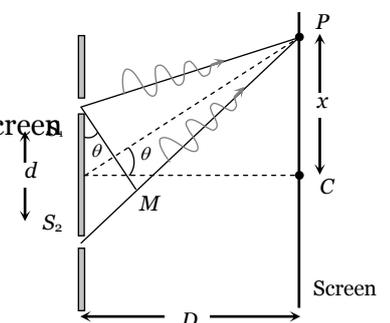
(6) **Path difference**

Path difference between the interfering waves meeting at a point P on the screen is given by $\Delta = \frac{xd}{D} = d\sin\theta$

where x is the position of point P from central maxima.

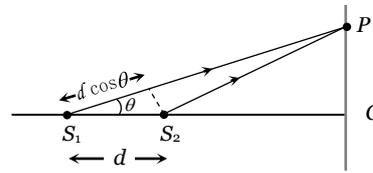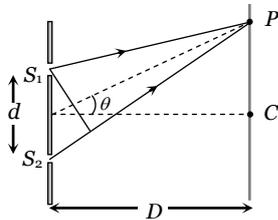For maxima at P: $\Delta = n\lambda$; where $n = 0, \pm 1, \pm 2, \dots\dots$

and For minima at P : $\quad \Delta = \dfrac{(2n-1)\lambda}{2}$; where $n = \pm 1, \pm 2, ...$

Note : ❑ If the slits are vertical, the path difference (Δ) is $d\sin\theta$, so as θ increases, Δ also increases.

But if slits are horizontal path difference is $d\cos\theta$, so as θ increases, Δ decreases.

(7) More about fringe

(i) All fringes are of

equal width. Width of each fringe is $\boldsymbol{\beta} = \dfrac{\boldsymbol{\lambda D}}{\boldsymbol{d}}$ and angular fringe width $\boldsymbol{\theta} = \dfrac{\boldsymbol{\lambda}}{\boldsymbol{d}} = \dfrac{\boldsymbol{\beta}}{\boldsymbol{D}}$

(ii) If the whole YDSE set up is taken in another medium then λ changes so β changes

e.g. in water $\lambda_w = \dfrac{\lambda_a}{\mu_w} \Rightarrow \beta_w = \dfrac{\beta_a}{\mu_w} = \dfrac{3}{4}\beta_a$

(iii) Fringe width $\beta \propto \dfrac{1}{d}$ *i.e.* with increase in separation between the sources, β decreases.

(iv) Position of nth bright fringe from central maxima $\boldsymbol{x_n} = \dfrac{\boldsymbol{n\lambda D}}{\boldsymbol{d}} = \boldsymbol{n\beta}$; $n = 0, 1, 2....$

(v) Position of nth dark fringe from central maxima $\boldsymbol{x_n} = \dfrac{\boldsymbol{(2n-1)\lambda D}}{\boldsymbol{2d}} = \dfrac{\boldsymbol{(2n-1)\beta}}{\boldsymbol{2}}$; $n = 1, 2, 3....$

(vi) In YDSE, if n_1 fringes are visible in a field of view with light of wavelength λ_1, while n_2 with light of wavelength λ_2 in the same field, then $\boldsymbol{n_1\lambda_1 = n_2\lambda_2}$.

(vii) Separation (Δx) between fringes

Between n^{th} bright and m^{th} bright fringes $(n > m)$	Between n^{th} bright and m^{th} dark fringe
$\Delta x = (n-m)\beta$	(a) If $n > m$ then $\Delta x = \left(n - m + \dfrac{1}{2}\right)\beta$
	(b) If $n < m$ then $\Delta x = \left(m - n - \dfrac{1}{2}\right)\beta$

(8) Identification of central bright fringe

To identify central bright fringe, monochromatic light is replaced by white light. Due to overlapping central maxima will be white with red edges. On the other side of it we shall get a few coloured band and then uniform illumination.

(9) Condition for observing sustained interference

(i) The initial phase difference between the interfering waves must remain constant : Otherwise the interference will not be sustained.

(ii) The frequency and wavelengths of two waves should be equal : If not the phase difference will not remain constant and so the interference will not be sustained.

(iii) The light must be monochromatic : This eliminates overlapping of patterns as each wavelength corresponds to one interference pattern.

(iv) The amplitudes of the waves must be equal : This improves contrast with $I_{max} = 4I_0$ and $I_{min} = 0$.

(v) The sources must be close to each other : Otherwise due to small fringe width $\left(\beta \propto \dfrac{1}{d} \right)$ the eye can not resolve fringes resulting in uniform illumination.

(10) Shifting of fringe pattern in YDSE

If a transparent thin film of mica or glass is put in the path of one of the waves, then the whole fringe pattern gets shifted.

If film is put in the path of upper wave, fringe pattern shifts upward and if film is placed in the path of lower wave, pattern shift downward.
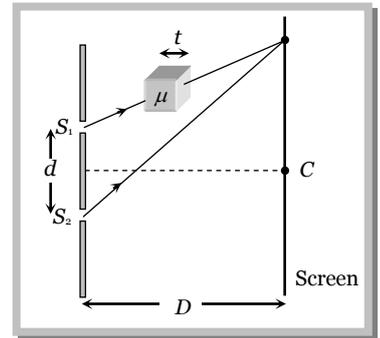
$$\text{Fringe shift} = \frac{D}{d}(\mu-1)t = \frac{\beta}{\lambda}(\mu-1)t$$

$\Rightarrow$ Additional path difference $= (\mu-1)t$

$\Rightarrow$ If shift is equivalent to n fringes then $n = \dfrac{(\mu-1)t}{\lambda}$ or $t = \dfrac{n\lambda}{(\mu-1)}$

$\Rightarrow$ Shift is independent of the order of fringe (*i.e.* shift of zero order maxima = shift of nth order maxima.

$\Rightarrow$ Shift is independent of wavelength.

Illustrations of Interference

Interference effects are commonly observed in thin films when their thickness is comparable to wavelength of incident light (If it is too thin as compared to wavelength of light it appears dark and if it is too thick, this will result in uniform illumination of film). Thin layer of oil on water surface and soap bubbles shows various colours in white light due to interference of waves reflected from the two surfaces of the film.
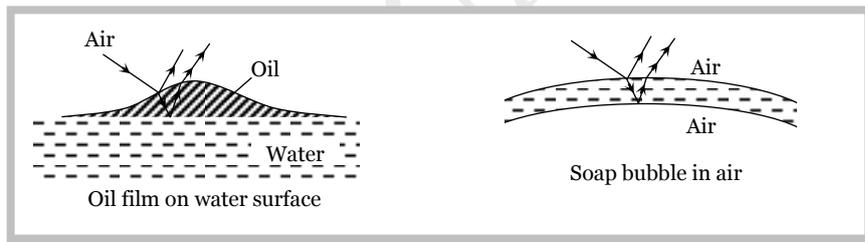
(1) **Thin films :** In thin films interference takes place between the waves reflected from it's two surfaces and waves refracted through it.
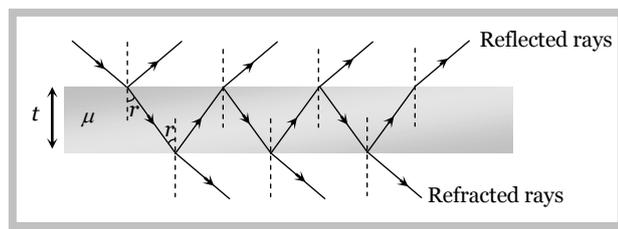
Interference in reflected light	Interference in refracted light
Condition of constructive interference (maximum intensity)	Condition of constructive interference (maximum intensity)
$\Delta = 2\mu\, t \cos r = (2n \pm 1)\dfrac{\lambda}{2}$	$\Delta = 2\mu\, t \cos r = (2n)\dfrac{\lambda}{2}$
For normal incidence $r = 0$	For normal incidence
so $2\mu t = (2n \pm 1)\dfrac{\lambda}{2}$	$2\mu t = n\lambda$

Condition of destructive interference (minimum intensity)	Condition of destructive interference (minimum intensity)
$\Delta = 2\mu t \cos r = (2n)\dfrac{\lambda}{2}$	$\Delta = 2\mu t \cos r = (2n \pm 1)\dfrac{\lambda}{2}$
For normal incidence $2\mu t = n\lambda$	For normal incidence $2\mu t = (2n \pm 1)\dfrac{\lambda}{2}$

Doppler's Effect in Light

The phenomenon of apparent change in frequency (or wavelength) of the light due to relative motion between the source of light and the observer is called Doppler's effect.

If ν = actual frequency, ν' = Apparent frequency, v = speed of source *w.r.t* stationary observer, c = speed of light

Source of light moves towards the stationary observer ($v << c$)	**Source of light moves away from the stationary observer ($v << c$)**
(i) Apparent frequency $\nu' = \nu\left(1 + \dfrac{v}{c}\right)$ and Apparent wavelength $\lambda' = \lambda\left(1 - \dfrac{v}{c}\right)$	(i) Apparent frequency $\nu' = \nu\left(1 - \dfrac{v}{c}\right)$ and Apparent wavelength $\lambda' = \lambda\left(1 + \dfrac{v}{c}\right)$
(ii) Doppler's shift : Apparent wavelength < actual wavelength, So spectrum of the radiation from the source of light shifts towards the red end of spectrum. This is called Red shift Doppler's shift $\Delta\lambda = \lambda.\dfrac{v}{c}$	(ii) Doppler's shift : Apparent wavelength > actual wavelength, So spectrum of the radiation from the source of light shifts towards the violet end of spectrum. This is called Violet shift Doppler's shift $\Delta\lambda = \lambda.\dfrac{v}{c}$

Note : ❑ Doppler's shift ($\Delta\lambda$) and time period of rotation (T) of a star relates as $\Delta\lambda = \dfrac{\lambda}{c} \times \dfrac{2\pi r}{T}$; r = radius of star.

Applications of Doppler effect
(i) Determination of speed of moving bodies (aeroplane, submarine etc) in RADAR and SONAR.
(ii) Determination of the velocities of stars and galaxies by spectral shift.
(iii) Determination of rotational motion of sun.
(iv) Explanation of width of spectral lines.
(v) Tracking of satellites.   (vi) In medical sciences in echo cardiogram, sonography *etc*.

Concepts

☞ *The angular thickness of fringe width is defined as $\delta = \dfrac{\beta}{D} = \dfrac{\lambda}{d}$, which is independent of the screen distance D.*

☞ *Central maxima means the maxima formed with zero optical path difference. It may be formed anywhere on the screen.*

☞ *All the wavelengths produce their central maxima at the same position.*

☞ *The wave with smaller wavelength from its maxima before the wave with longer wavelength.*

☞ *The first maxima of violet colour is closest and that for the red colour is farthest.*

☞ *Fringes with blue light are thicker than those for red light.*

☞ *In an interference pattern, whatever energy disappears at the minimum, appears at the maximum.*

☞ *In YDSE, the nth maxima always comes before the nth minima.*

☞ *In YDSE, the ratio $\dfrac{I_{\max}}{I_{\min}}$ is maximum when both the sources have same intensity.*

☞ *For two interfering waves if initial phase difference between them is ϕ_0 and phase difference due to path difference between them is ϕ'. Then total phase difference will be $\phi = \phi_0 + \phi' = \phi_0 + \dfrac{2\pi}{\lambda}\Delta$.*

☞ *Sometimes maximm number of maximas or minimas are asked in the question which can be obtained on the screen. For this we use the fact that value of sin θ (or cos θ) can't be greater than 1. For example in the first case when the slits are vertical*

$$\sin\theta = \frac{n\lambda}{d} \qquad \text{(for maximum intensity)}$$

$$\because \qquad \sin\theta \not> 1 \qquad \therefore \qquad \frac{n\lambda}{d} \not> 1 \quad or \quad n \not> \frac{d}{\lambda}$$

Suppose in some question d/λ comes out say 4.6, then total number of maximuas on the screen will be 9. Corresponding to $n = 0, \pm 1, \pm 2, \pm 3$ and ± 4.

☞ **Shape of wave front**

If rays are parallel, wave front is plane. If rays are converging wave front is spherical of decreasing radius. If rays are diverging wave front is spherical of increasing radius.

❑ The minimum distance at which the observer should be from the obstacle to observe the diffraction of light of wavelength λ around the obstacle of size d is given by $x = \dfrac{d^2}{4\lambda}$.

(1) **Types of diffraction :** The diffraction phenomenon is divided into two types

Fresnel diffraction	Fraunhofer diffraction
(i) If either source or screen or both are at finite distance from the diffracting device (obstacle or aperture), the diffraction is called Fresnel type.	(i) In this case both source and screen are effectively at infinite distance from the diffracting device.
(ii) Common examples : Diffraction at a straight edge, narrow wire or small opaque disc etc.	(ii) Common examples : Diffraction at single slit, double slit and diffraction grating.
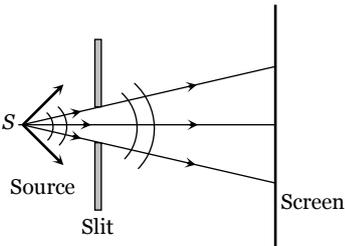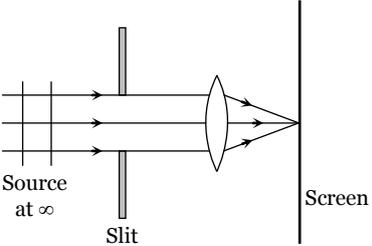
(2) **Diffraction of light at a single slit :** In case of diffraction at a single slit, we get a central bright band with alternate bright (maxima) and dark (minima) bands of decreasing intensity as shown
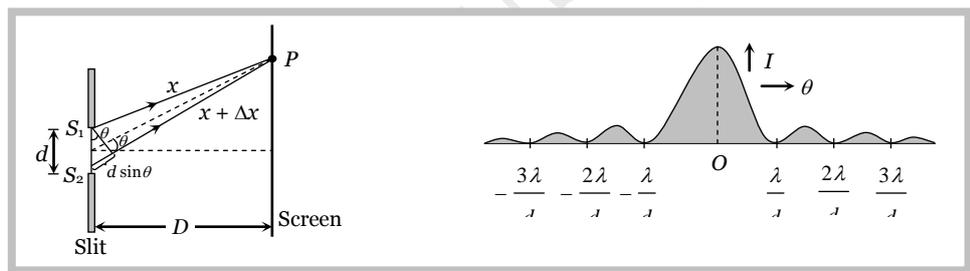
(i) Width of central maxima $\beta_0 = \dfrac{2\lambda D}{d}$, and angular width $= \dfrac{2\lambda}{d}$

(ii) Minima occurs at a point on either side of the central maxima, such that the path difference between the waves from the two ends of the aperture is given by $\Delta = n\lambda$; where $n = 1, 2, 3 \ldots$

i.e. $d\sin\theta = n\lambda \Rightarrow \sin\theta = \dfrac{n\lambda}{d}$

(iii) The secondary maxima occurs, where the path difference between the waves from the two ends of the aperture is given by $\Delta = (2n+1)\dfrac{\lambda}{2}$; where $n = 1, 2, 3 \ldots$

i.e. $d\sin\theta = (2n+1)\dfrac{\lambda}{2} \Rightarrow \sin\theta = \dfrac{(2n+1)\lambda}{2d}$

(3) **Comparison between interference and diffraction**

Interference	Diffraction
Results due to the superposition of waves from two coherrent sources.	Results due to the superposition of wavelets from different parts of same wave front. (single coherent source)

All fringes are of same width $\beta = \dfrac{\lambda D}{d}$	All secondary fringes are of same width but the central maximum is of double the width $$\beta_0 = 2\beta = 2\dfrac{\lambda D}{d}$$
All fringes are of same intensity	Intensity decreases as the order of maximum increases.
Intensity of all minimum may be zero	Intensity of minima is not zero.
Positions of nth maxima and minima $$x_{n(\text{Bright})} = \dfrac{n\lambda D}{d}, \quad x_{n(\text{Dark})} = (2n-1)\dfrac{\lambda D}{d}$$	Positions of nth secondary maxima and minima $$x_{n(\text{Bright})} = (2n+1)\dfrac{\lambda D}{d}, \quad x_{n(\text{Dark})} = \dfrac{n\lambda D}{d}$$
Path difference for nth maxima $\Delta = n\lambda$	for nth secondary maxima $\Delta = (2n+1)\dfrac{\lambda}{2}$
Path difference for nth minima $\Delta = (2n-1)\lambda$	Path difference for nth minima $\Delta = n\lambda$

(4) **Diffraction and optical instruments :** The objective lens of optical instrument like telescope or microscope etc. acts like a circular aperture. Due to diffraction of light at a circular aperture, a converging lens cannot form a point image of an object rather it produces a brighter disc known as Airy disc surrounded by alternate dark and bright concentric rings.
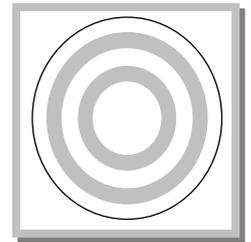
The angular half width of Airy disc $= \theta = \dfrac{1.22\lambda}{D}$ (where D = aperture of lens)

The lateral width of the image $= f\theta$ (where f = focal length of the lens)

Note : ❑ Diffraction of light limits the ability of optical instruments to form clear images of objects when they are close to each other.

(5) **Diffraction grating :** Consists of large number of equally spaced parallel slits. If light is incident normally on a transmission grating, the diffraction of principle maxima (*PM*) is given by $d\sin\theta = n\lambda$; where d = distance between two consecutive slits and is called grating element.
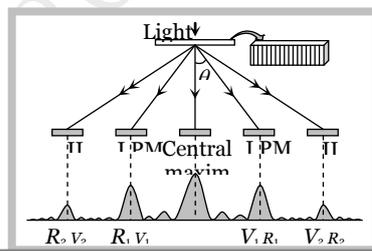
Polarisation of Light

Light propagates as transverse EM waves. The magnitude of electric field is much larger as compared to magnitude of magnetic field. We generally prefer to describe light as electric field oscillations.

(1) **Unpolarised light**

The light having electric field oscillations in all directions in the plane perpendicular to the direction of propagation is called Unpolarised light. The oscillation may be resolved into horizontal and vertical component.

(2)
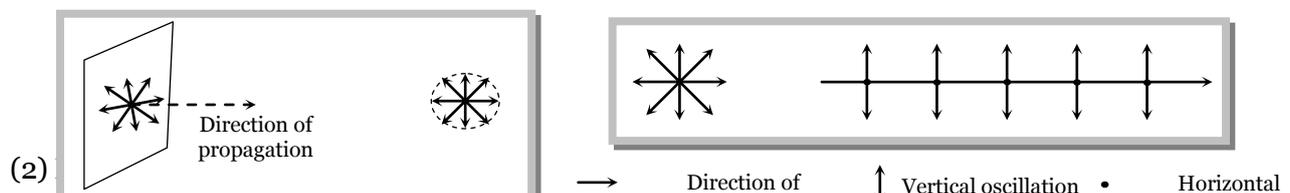
The light having oscillations only in one plane is called Polarised or plane polarised light.

(i) The plane in which oscillation occurs in the polarised light is called plane of oscillation.

(ii) The plane perpendicular to the plane of oscillation is called plane of polarisation.

(iii) Light can be polarised by transmitting through certain crystals such as tourmaline or polaroids.
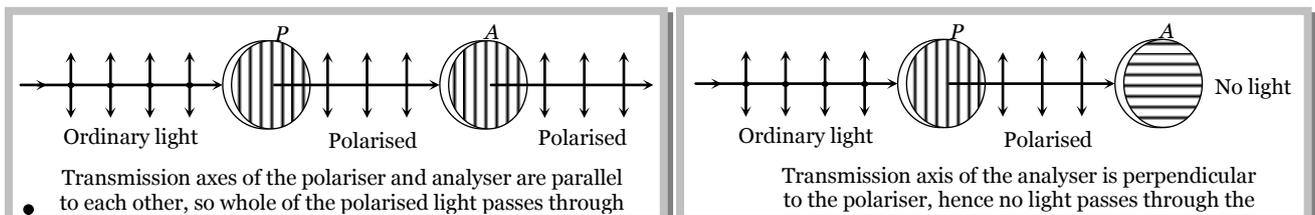
(3) Polaroids

It is a device used to produce the plane polarised light. It is based on the principle of selective absorption and is more effective than the tourmaline crystal. or

It is a thin film of ultramicroscopic crystals of quinine idosulphate with their optic axis parallel to each other.
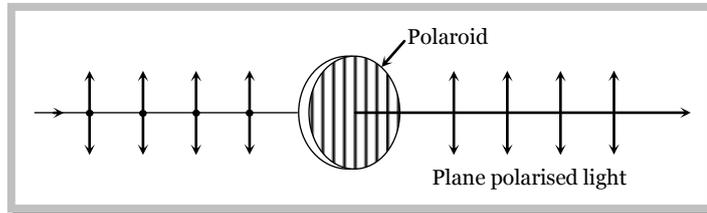

(i) Polaroids allow the light oscillations parallel to the transmission axis pass through them.

(ii) The crystal or polaroid on which unpolarised light is incident is called polariser. Crystal or polaroid on which polarised light is incident is called analyser.

Transmission axes of the polariser and analyser are parallel to each other, so whole of the polarised light passes through

Transmission axis of the analyser is perpendicular to the polariser, hence no light passes through the

Note : ❑ When unpolarised light is incident on the polariser, the intensity of the transmitted polarised light is half the intensity of unpolarised light.

(4) **Malus law** This law states that the intensity of the polarised light transmitted through the analyser varies as the square of the cosine of the angle between the plane of transmission of the analyser and the plane of the polariser.
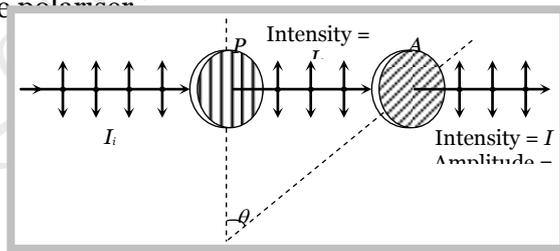
(i) $I = I_0 \cos^2 \theta$ and $A^2 = A_0^2 \cos^2 \theta \Rightarrow A = A_0 \cos \theta$

If $\theta = 0^o$, $I = I_0$, $A = A_0$,   If $\theta = 45^o$, $I = \dfrac{I_0}{2}$, $A = \dfrac{A_0}{\sqrt{2}}$,   If $\theta = 90^o$, $I = 0$, $A = 0$

(ii) If $I_i =$ Intensity of unpolarised light.

So $I_0 = \dfrac{I_i}{2}$ *i.e.* if an unpolarised light is converted into plane polarised light (say by passing it through a plaroid or a Nicol-prism), its intensity becomes half. and $I = \dfrac{I_i}{2} \cos^2 \theta$

Note : ❑ Percentage of polarisation $= \dfrac{(I_{\max} - I_{\min})}{(I_{\max} + I_{\min})} \times 100$

(5) **Brewster's law :** Brewster discovered that when a beam of unpolarised light is reflected from a transparent medium (refractive index $= \mu$), the reflected light is completely plane polarised at a certain angle of incidence (called the angle of polarisation θ_p).
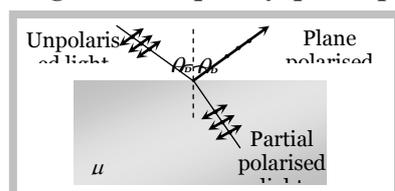
Also $\mu = \tan \theta_p$ Brewster's law

(i) For $i < \theta_P$ or $i > \theta_P$

Both reflected and refracted rays becomes partially polarised

(ii) For glass $\theta_P \approx 57^o$, for water $\theta_P \approx 53^o$

(6) **Optical activity and specific rotation**

When plane polarised light passes through certain substances, the plane of polarisation of the light is rotated about the direction of propagation of light through a certain angle. This phenomenon is called optical activity or optical rotation and the substances optically active.

If the optically active substance rotates the plane of polarisation clockwise (looking against the direction of light), it is said to be *dextro-rotatory* or *right-handed.* However, if the substance rotates the plane of polarisation anti-clockwise, it is called *laevo-rotatory* or *left-handed.*
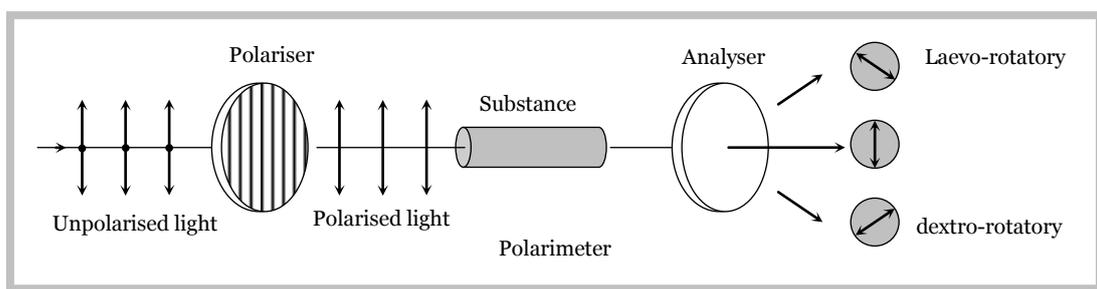
The optical activity of a substance is related to the asymmetry of the molecule or crystal as a whole, *e.g.*, a solution of cane-sugar is dextro-rotatory due to asymmetrical molecular structure while crystals of quartz are dextro or laevo-rotatory due to structural asymmetry which vanishes when quartz is fused.

Optical activity of a substance is measured with help of polarimeter in terms of 'specific rotation' which is defined as the rotation produced by a solution of length 10 *cm* (1 *dm*) and of unit concentration (*i.e.* 1 *g*/cc) for a given wavelength of light at a given temperature. *i.e.* $[\alpha]^{\lambda}_{t^oC} = \dfrac{\theta}{L \times C}$ where θ is the rotation in length *L* at concentration *C*.

(7) **Applications and uses of polarisation**

(i) By determining the polarising angle and using Brewster's law, *i.e.* $\mu = \tan\theta_P$, refractive index of dark transparent substance can be determined.

(ii) It is used to reduce glare.

(iii) In calculators and watches, numbers and letters are formed by liquid crystals through polarisation of light called liquid crystal display **(LCD)**.

(iv) In CD player polarised laser beam acts as needle for producing sound from compact disc which is an encoded digital format.

(v) It has also been used in recording and reproducing three-dimensional pictures.

(vi) Polarisation of scattered sunlight is used for navigation in solar-compass in polar regions.

(vii) Polarised light is used in optical stress analysis known as 'photoelasticity'.

(viii) Polarisation is also used to study asymmetries in molecules and crystals through the phenomenon of 'optical activity'.