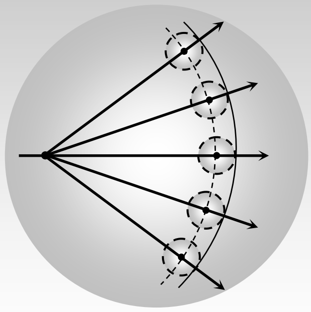


Wave Optics

Light Propagation

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

(1) **Different theories**

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 $c = \frac{1}{\sqrt{\mu_0 \varepsilon_0}}$	(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 $E = h\nu = \frac{hc}{\lambda}$ 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 (micro-scopic particles)

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

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	×	×	×	√	√

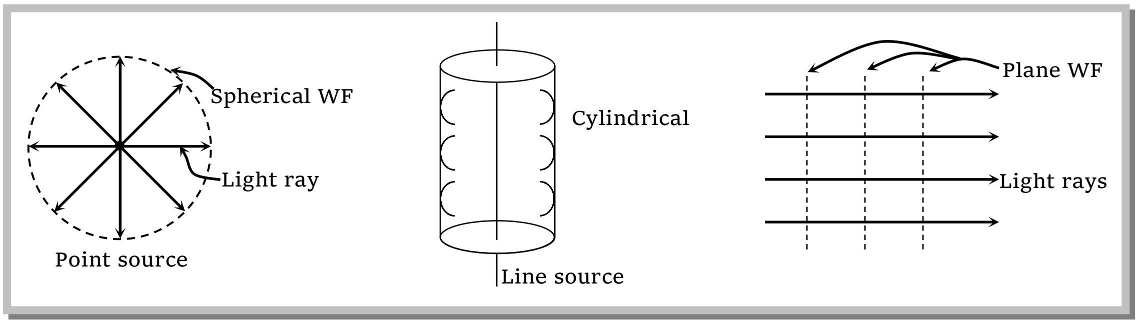
(3) **Wave front**

(i) Suggested by Huygens

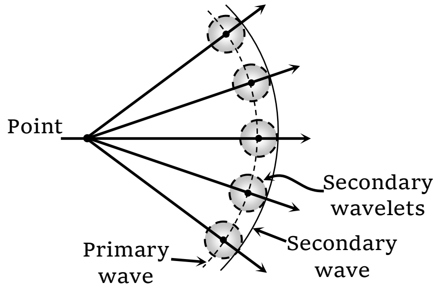
(ii) The locus of all particles in a medium, vibrating in the same phase is called Wave Front (WF)

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

(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.

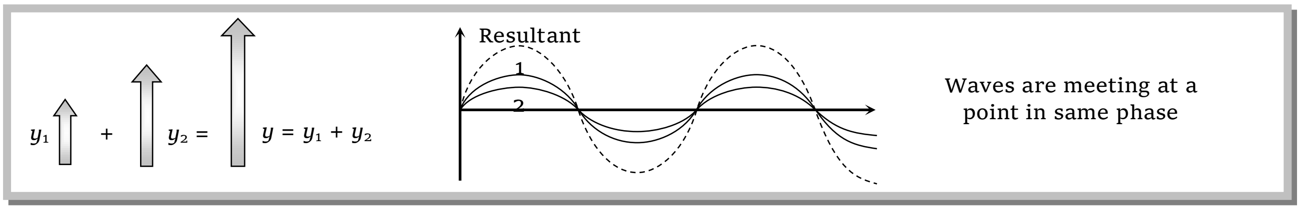
❑ The phase difference between various particles on the wave front is zero.

Principle of Super Position

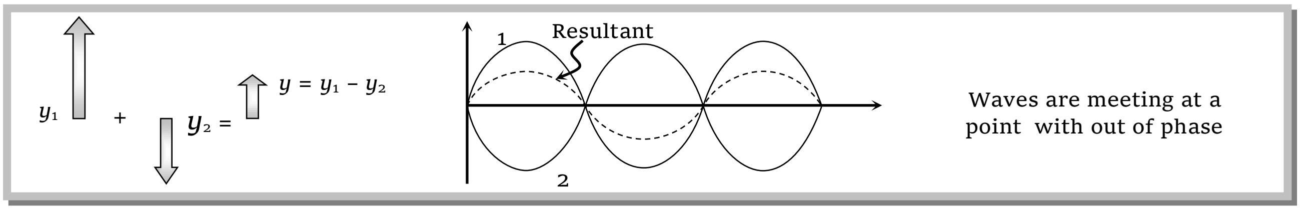
When two or more than two waves superimpose over each other at a common particle of the medium then the resultant displacement (y) of the particle is equal to the vector sum of the displacements (y_1 and y_2) produced by individual waves. *i.e.* $\vec{y} = \vec{y}_1 + \vec{y}_2$

(1) **Graphical view :**

(i)



(ii)



(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 $\Delta = \frac{\lambda}{2\pi} \times \phi$

(iv) Time difference ($T.D.$) : Time difference between the waves meeting at a point is $T.D. = \frac{T}{2\pi} \times \phi$

(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 $A = \sqrt{a_1^2 + a_2^2 + 2a_1a_2\cos\phi}$

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 $A = \sqrt{a_1^2 + a_2^2}$

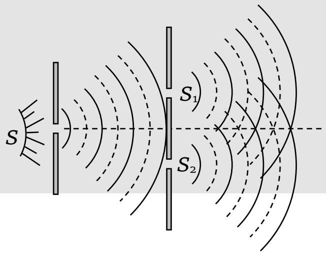
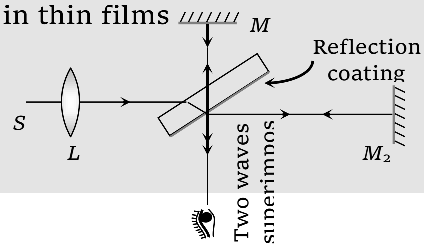
Resultant intensity : As we know intensity $\propto$ (Amplitude)² $\Rightarrow I_1 = ka_1^2, I_2 = ka_2^2$ and $I = kA^2$ (k is a proportionality constant). Hence from the formula of resultant amplitude, we get the following formula of resultant intensity $I = I_1 + I_2 + 2\sqrt{I_1 I_2}\cos\phi$

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

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 

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 $\tau_c = \frac{L}{c} = \frac{\text{Distance of coherence}}{\text{Velocity of light}}$, 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) $\Delta = (2n-1)\frac{\lambda}{2}$ (*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 $I_1 = I_2 = I_0 \Rightarrow I = I_0 + I_0 + 2\sqrt{I_0 I_0}\cos\phi = 4I_0\cos^2\frac{\phi}{2}$ [1 + cosθ $= 2\cos^2\frac{\theta}{2}$]

Note :
- In interference redistribution of energy takes place in the form of maxima and minima.
- Average intensity : $I_{av} = \frac{I_{\max} + I_{\min}}{2} = I_1 + I_2 = a_1^2 + a_2^2$
- Ratio of maximum and minimum intensities :

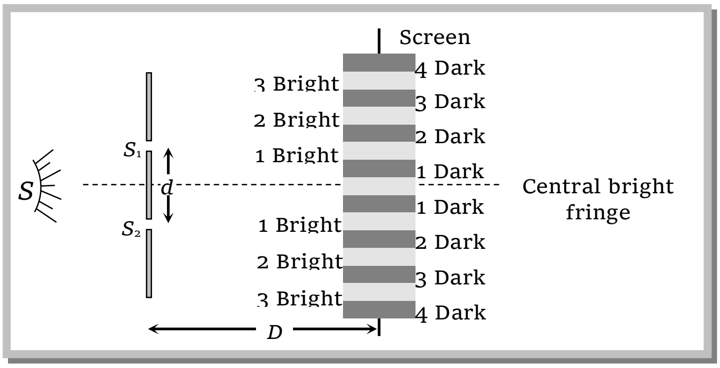
$$\frac{I_{\max}}{I_{\min}} = \left(\frac{\sqrt{I_1} + \sqrt{I_2}}{\sqrt{I_1} - \sqrt{I_2}}\right)^2 = \left(\frac{\sqrt{I_1/I_2} + 1}{\sqrt{I_1/I_2} - 1}\right)^2 = \left(\frac{a_1 + a_2}{a_1 - a_2}\right)^2 = \left(\frac{a_1/a_2 + 1}{a_1/a_2 - 1}\right)^2 \text{ also } \sqrt{\frac{I_1}{I_2}} = \frac{a_1}{a_2}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

- 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



(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.

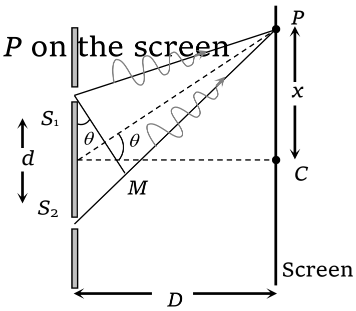
(3) If the slit widths are unequal, the minima will not be complete dark. For very large width uniform illumination occurs.

(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 $\Delta = \frac{xd}{D} = d\sin\theta$

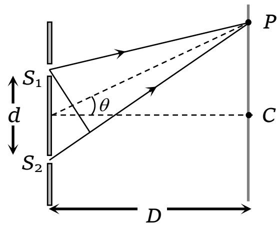


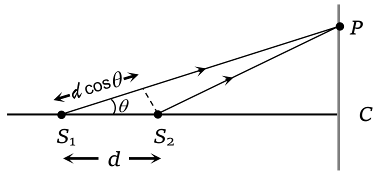
where x is the position of point P from central maxima.

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

and For minima at P : $\Delta = \frac{(2n-1)\lambda}{2}$; where n = ± 1, ± 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 $\boldsymbol{\beta = \frac{\lambda D}{d}}$ and angular fringe width $\boldsymbol{\theta = \frac{\lambda}{d} = \frac{\beta}{D}}$

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

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

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

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

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

(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 $\Delta x = \left(n - m + \frac{1}{2}\right)\beta$ (b) If $n < m$ then $\Delta x = \left(m - n - \frac{1}{2}\right)\beta$

(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.

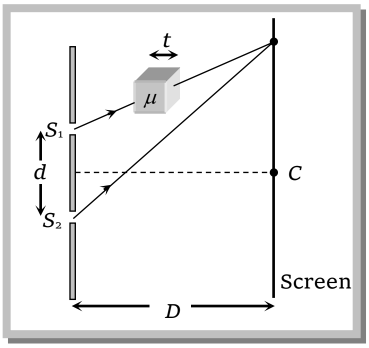
(iii) The light must be monochromatic : This eliminates overlapping of patterns as each wavelength corresponds to one interference pattern.

(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 $\left(\beta \propto \frac{1}{d}\right)$ 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.

$$\text{Fringe shift} = \frac{D}{d}(\mu-1)t = \frac{\beta}{\lambda}(\mu-1)t$$

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

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

⇒ Shift is independent of the order of fringe (*i.e.* shift of zero order maxima = shift of n^{th} order maxima.

⇒ Shift is independent of wavelength.

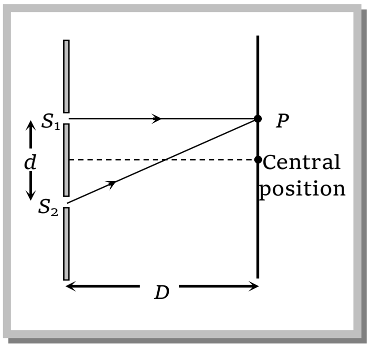
(11) **Fringe visibility (V)**

With the help of visibility, knowledge about coherence, fringe contrast an interference pattern is obtained.

$$V = \frac{I_{max} - I_{min}}{I_{max} + I_{min}} = 2\frac{\sqrt{I_1 I_2}}{(I_1 + I_2)}$$ If $I_{min} = 0$, $V = 1$ (maximum) *i.e.*, fringe visibility will be best.

Also if $I_{max} = 0, V = -1$ and If $I_{max} = I_{min}, V = 0$

(12) **Missing wavelength in front of one of the slits in YDSE**



From figure $S_2P = \sqrt{D^2 + d^2}$ and $S_1P = D$

So the path difference between the waves reaching at P

$$\Delta = S_2P - S_1P = \sqrt{D^2 + d^2} - D = D\left(1 + \frac{d^2}{D^2}\right)^{1/2} - D$$

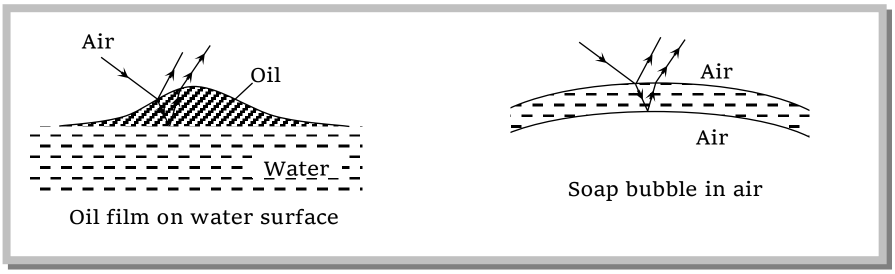
From binomial expansion $\Delta = D\left(1 + \frac{1}{2}\frac{d^2}{D^2}\right) - D = \frac{d^2}{2D}$

For Dark at P $\Delta = \frac{d^2}{2D} = \frac{(2n-1)\lambda}{2}$ ⇒ Missing wavelength at P $\boldsymbol{\lambda = \frac{d^2}{(2n-1)D}}$

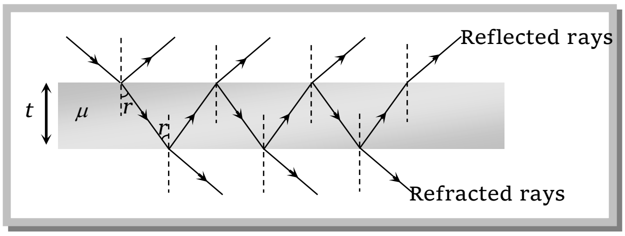
By putting $n = 1, 2, 3....$ Missing wavelengths are $\lambda = \frac{d^2}{D}, \frac{d^2}{3D}, \frac{d^2}{5D}....$

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.



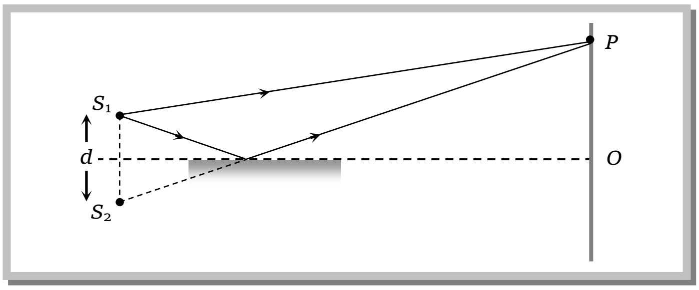
Interference in reflected light	Interference in refracted light
Condition of constructive interference (maximum intensity) $\Delta = 2\mu\ t\cos r = (2n \pm 1)\frac{\lambda}{2}$ For normal incidence $r = 0$ so $2\mu t = (2n \pm 1)\frac{\lambda}{2}$	Condition of constructive interference (maximum intensity) $\Delta = 2\mu t\cos r = (2n)\frac{\lambda}{2}$ For normal incidence $2\mu t = n\lambda$
Condition of destructive interference (minimum intensity) $\Delta = 2\mu t\cos r = (2n)\frac{\lambda}{2}$ For normal incidence $2\mu t = n\lambda$	Condition of destructive interference (minimum intensity) $\Delta = 2\mu t\cos r = (2n \pm 1)\frac{\lambda}{2}$ For normal incidence $2\mu t = (2n \pm 1)\frac{\lambda}{2}$

Note : ❑ The Thickness of the film for interference in visible light is of the order of $10,000\ \mathring{A}$.

(2) **Lloyd's Mirror**

A plane glass plate (acting as a mirror) is illuminated at almost grazing incidence by a light from a slit S_1. A virtual image S_2 of S_1 is formed closed to S_1 by reflection and these two act as coherent sources. The expression giving the fringe width is the same as for the double slit, but the fringe system differs in one important respect.

In Lloyd's mirror, if the point *P*, for example, is such that the path difference $S_2P - S_1P$ is a whole number of wavelengths, the fringe at *P* is dark not bright. This is due to 180° phase change which occurs when light is reflected from a denser medium. This is equivalent to adding an extra half wavelength to the path of the reflected wave. At grazing incidence a fringe is formed at *O*, where the geometrical path difference between the direct and reflected waves is zero and it follows that it will be dark rather than bright.



Thus, whenever there exists a phase difference of a π between the two interfering beams of light, conditions of maximas and minimas are interchanged, *i.e.*, $\Delta x = n\lambda$ (for minimum intensity)

and $\Delta x = (2n-1)\lambda/2$ (for maximum intensity)

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 $\nu =$ actual frequency, $\nu' =$ 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 $\nu' = \nu\left(1+\frac{v}{c}\right)$ and Apparent wavelength $\lambda' = \lambda\left(1-\frac{v}{c}\right)$	(i) Apparent frequency $\nu' = \nu\left(1-\frac{v}{c}\right)$ and Apparent wavelength $\lambda' = \lambda\left(1+\frac{v}{c}\right)$
(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	(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 $\Delta\lambda = \lambda.\frac{v}{c}$	Doppler's shift $\Delta\lambda = \lambda.\frac{v}{c}$

Note : ❑ Doppler's shift $(\Delta\lambda)$ and time period of rotation (T) of a star relates as $\Delta\lambda = \frac{\lambda}{c} \times \frac{2\pi r}{T}$; 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* $\delta = \frac{\beta}{D} = \frac{\lambda}{d}$, *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* $\frac{I_{\max}}{I_{\min}}$ *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* $\phi = \phi_0 + \phi' = \phi_0 + \frac{2\pi}{\lambda}\Delta$.

☞ *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*

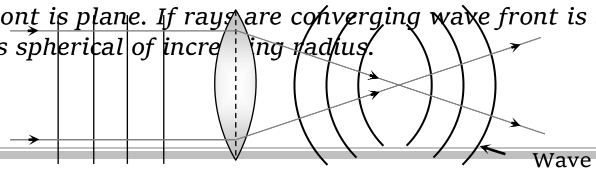
$$\sin\theta = \frac{n\lambda}{d} \qquad \textit{(for maximum intensity)}$$

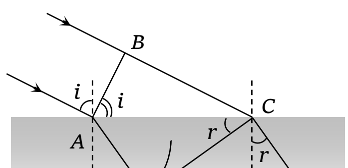
$$\because \quad \sin\theta \not> 1 \qquad \therefore \quad \frac{n\lambda}{d} \not> 1 \quad \text{or} \quad n \not> \frac{d}{\lambda}$$

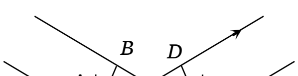
Suppose in some question d/λ comes out say 4.6, then total number of maximuas on the screen will be 9. Corresponding to $n = 0, \pm1, \pm2, \pm3$ *and* ±4.

☞ ***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.







☞ *Reflection and refraction of wave front*

Reflection	*Refraction*
$BC = AD$ and $\angle i = \angle r$	$\dfrac{BC}{AD} = \dfrac{v_1}{v_2} = \dfrac{\sin i}{\sin r} = \dfrac{\mu_2}{\mu_1}$

Example

***Example*: 1** If two light waves having same frequency have intensity ratio 4 : 1 and they interfere, the ratio of maximum to minimum intensity in the pattern will be

(a) 9 : 1 (b) 3 : 1 (c) 25 : 9 (d) 16 : 25

Solution: (a) By using $\dfrac{I_{max}}{I_{min}} = \left(\dfrac{\sqrt{\dfrac{I_1}{I_2}}+1}{\sqrt{\dfrac{I_1}{I_2}}-1}\right)^2 = \left(\dfrac{\sqrt{\dfrac{4}{1}}+1}{\sqrt{\dfrac{4}{1}}-1}\right)^2 = \dfrac{9}{1}$.

***Example*: 2** In Young's double slit experiment using sodium light (λ = 5898$\mathring{A}$), 92 fringes are seen. If given colour (λ = 5461$\mathring{A}$) is used, how many fringes will be seen

(a) 62 (b) 67 (c) 85 (d) 99

Solution: (d) By using $n_1\lambda_1 = n_2\lambda_2 \Rightarrow 92 \times 5898 = n_2 \times 5461 \Rightarrow n_2 = 99$

***Example*: 3** Two beams of light having intensities I and $4I$ interfere to produce a fringe pattern on a screen. The phase difference between the beams is $\dfrac{\pi}{2}$ at point A and π at point B. Then the difference between the resultant intensities at A and B is

(a) $2I$ (b) $4I$ (c) $5I$ (d) $7I$

Solution: (b) By using $I = I_1 + I_2 + 2\sqrt{I_1 I_2}\cos\phi$

At point A : Resultant intensity $I_A = I + 4I + 2\sqrt{I \times 4I}\cos\dfrac{\pi}{2} = 5I$

At point B : Resultant intensity $I_B = I + 4I + 2\sqrt{I \times 4I}\cos\pi = I$. Hence the difference $= I_A - I_B = 4I$

Example: 4 If two waves represented by $y_1 = 4\sin\omega t$ and $y_2 = 3\sin\left(\omega t + \frac{\pi}{3}\right)$ interfere at a point, the amplitude of the resulting wave will be about

(a) 7 (b) 6 (c) 5 (d) 3.

Solution: (b) By using $A = \sqrt{a_1^2 + a_2^2 + 2a_1a_2\cos\phi}$ $\Rightarrow$ $A = \sqrt{(4)^2 + (3)^2 + 2\times 4\times 3\cos\frac{\pi}{3}} = \sqrt{37} \approx 6$.

Example: 5 Two waves being produced by two sources S_1 and S_2. Both sources have zero phase difference and have wavelength λ. The destructive interference of both the waves will occur of point *P* if $(S_1P - S_2P)$ has the value

[MP PET 1987]

(a) 5λ (b) $\frac{3}{4}\lambda$ (c) 2λ (d) $\frac{11}{2}\lambda$

Solution: (d) For destructive interference, path difference the waves meeting at *P* (*i.e.* $S_1P - S_2P$) must be odd multiple of $\lambda/2$. Hence option (d) is correct.

Example: 6 Two interfering wave (having intensities are 9*I* and 4*I*) path difference between them is 11 λ. The resultant intensity at this point will be

(a) I (b) $9\,I$ (c) $4\,I$ (d) $25\,I$

Solution: (d) Path difference $\Delta = \frac{\lambda}{2\pi}\times\phi$ $\Rightarrow$ $\frac{2\pi}{\lambda}\times 11\lambda = 22\pi$ *i.e.* constructive interference obtained at the same point

So, resultant intensity $I_R = (\sqrt{I_1} + \sqrt{I_2})^2 = (\sqrt{9I} + \sqrt{4I})^2 = 25\,I$.

Example: 7 In interference if $\frac{I_{max}}{I_{min}} = \frac{144}{81}$ then what will be the ratio of amplitudes of the interfering wave

(a) $\frac{144}{81}$ (b) $\frac{7}{1}$ (c) $\frac{1}{7}$ (d) $\frac{12}{9}$

Solution: (b) By using $\frac{a_1}{a_2} = \left(\frac{\sqrt{\frac{I_{max}}{I_{min}}} + 1}{\sqrt{\frac{I_{max}}{I_{min}}} - 1}\right) = \left(\frac{\sqrt{\frac{144}{81}} + 1}{\sqrt{\frac{144}{81}} - 1}\right) = \left(\frac{\frac{12}{9} + 1}{\frac{12}{5} - 1}\right) = \frac{7}{1}$

Example: 8 Two interfering waves having intensities *x* and *y* meets a point with time difference 3*T*/2. What will be the resultant intensity at that point

(a) $(\sqrt{x} + \sqrt{y})$ (b) $(\sqrt{x} + \sqrt{y} + \sqrt{xy})$ (c) $x + y + 2\sqrt{xy}$ (d) $\frac{x+y}{2xy}$

Solution: (c) Time difference T.D. $= \frac{T}{2\pi}\times\phi \Rightarrow \frac{3T}{2} = \frac{T}{2\pi}\times\phi \Rightarrow \phi = 3\pi$; This is the condition of constructive interference.

So resultant intensity $I_R = (\sqrt{I_1} + \sqrt{I_2})^2 = (\sqrt{x} + \sqrt{y})^2 = x + y + 2\sqrt{xy}$.

***Example*: 9** In Young's double-slit experiment, an interference pattern is obtained on a screen by a light of wavelength 6000 $\mathring{A}$, coming from the coherent sources S_1 and S_2. At certain point P on the screen third dark fringe is formed. Then the path difference $S_1P - S_2P$ in microns is

(a) 0.75 (b) 1.5 (c) 3.0 (d) 4.5

Solution: (b) For dark fringe path difference $\Delta = (2n-1)\frac{\lambda}{2}$; here n = 3 and λ = 6000 × 10^{-10} m

So $\Delta = (2\times 3-1)\times \frac{6\times 10^{-7}}{2} = 15\times 10^{-7}\, m = 1.5\, microns$.

***Example*: 10** In a Young's double slit experiment, the slit separation is 1 mm and the screen is 1 m from the slit. For a monochromatic light of wavelength 500 nm, the distance of 3rd minima from the central maxima is

(a) 0.50 mm (b) 1.25 mm (c) 1.50 mm (d) 1.75 mm

Solution: (b) Distance of n^{th} minima from central maxima is given as $x = \frac{(2n-1)\lambda D}{2d}$

So here $x = \frac{(2\times 3-1)\times 500\times 10^{-9}\times 1}{2\times 10^{-3}} = 1.25\, mm$

***Example*: 11** The two slits at a distance of 1 mm are illuminated by the light of wavelength 6.5×10^{-7} m. The interference fringes are observed on a screen placed at a distance of 1 m. The distance between third dark fringe and fifth bright fringe will be

[NCERT 1982; MP PET 1995; BVP 2003]

(a) 0.65 mm (b) 1.63 mm (c) 3.25 mm (d) 4.88 mm

Solution: (b) Distance between n^{th} bright and m^{th} dark fringe ($n > m$) is given as $x = \left(n-m+\frac{1}{2}\right)\beta = \left(n-m+\frac{1}{2}\right)\frac{\lambda D}{d}$

$\Rightarrow x = \left(5-3+\frac{1}{2}\right)\times \frac{6.5\times 10^{-7}\times 1}{1\times 10^{-3}} = 1.63\, mm$.

***Example*: 12** The slits in a Young's double slit experiment have equal widths and the source is placed symmetrically relative to the slits. The intensity at the central fringes is I_0. If one of the slits is closed, the intensity at this point will be **[MP PMT 1999]**

(a) I_0 (b) $I_0/4$ (c) $I_0/2$ (d) $4I_0$

Solution: (b) By using $I_R = 4I\cos^2\frac{\phi}{2}$ {where I = Intensity of each wave}

At central position ϕ = 0°, hence initially $I_0 = 4I$.

If one slit is closed, no interference takes place so intensity at the same location will be I only *i.e.* intensity become s$\frac{1}{4}th$ or $\frac{I_0}{4}$.

***Example*: 13** In double slit experiment, the angular width of the fringes is 0.20° for the sodium light (λ = 5890 $\mathring{A}$). In order to increase the angular width of the fringes by 10%, the necessary change in the wavelength is **[MP PMT 1997]**

(a) Increase of 589 $\mathring{A}$ (b) Decrease of 589 $\mathring{A}$ (c) Increase of 6479 $\mathring{A}$ (d)

Solution: (a) By using $\theta = \frac{\lambda}{d} \Rightarrow \frac{\theta_1}{\theta_2} = \frac{\lambda_1}{\lambda_2} \Rightarrow \frac{0.20^o}{(0.20^o + 10\% \text{ of } 0.20)} = \frac{5890}{\lambda_2} \Rightarrow \frac{0.20}{0.22} = \frac{5890}{\lambda_2} \Rightarrow \lambda_2 = 6479$

So increase in wavelength = 6479 – 5890 = 589 Å.

Example: 14 In Young's experiment, light of wavelength 4000 *Å* is used, and fringes are formed at 2 *metre* distance and has a fringe width of 0.6 *mm*. If whole of the experiment is performed in a liquid of refractive index 1.5, then width of fringe will be

[MP PMT 1994, 97]

(a) 0.2 *mm* (b) 0.3 *mm* (c) 0.4 *mm* (d) 1.2 *mm*

Solution: (c) $\beta_{medium} = \frac{\beta_{air}}{\mu} \Rightarrow \beta_{medium} = \frac{0.6}{1.5} = 0.4 mm$.

Example: 15 Two identical sources emitted waves which produces intensity of k unit at a point on screen where path difference is λ. What will be intensity at a point on screen at which path difference is $\lambda/4$ **[RPET 1996]**

(a) $\frac{k}{4}$ (b) $\frac{k}{2}$ (c) k (d) Zero

Solution: (b) By using phase difference $\phi = \frac{2\pi}{\lambda}(\Delta)$

For path difference λ, phase difference $\phi_1 = 2\pi$ and for path difference $\lambda/4$, phase difference $\phi_2 = \pi/2$.

Also by using $I = 4I_0 \cos^2 \frac{\phi}{2} \Rightarrow \frac{I_1}{I_2} = \frac{\cos^2(\phi_1/2)}{\cos^2(\phi_2/2)} \Rightarrow \frac{k}{I_2} = \frac{\cos^2(2\pi/2)}{\cos^2\left(\frac{\pi/2}{2}\right)} = \frac{1}{1/2} \Rightarrow I_2 = \frac{k}{2}$.

Example: 16 A thin mica sheet of thickness 2×10^{-6} m and refractive index (μ = 1.5) is introduced in the path of the first wave. The wavelength of the wave used is 5000*Å*. The central bright maximum will shift **[CPMT 1999]**

(a) 2 fringes upward (b) 2 fringes downward (c) 10 fringes upward (d)

Solution: (a) By using shift $\Delta x = \frac{p}{\lambda}(\mu - 1)t \Rightarrow \Delta x = \frac{\beta}{5000 \times 10^{-10}}(1.5 - 1) \times 2 \times 10^{-6} = 2\beta$

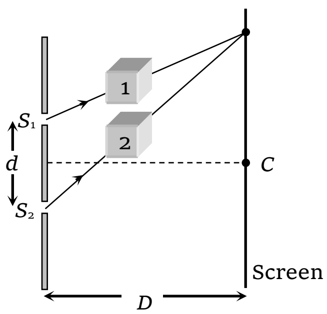
Since the sheet is placed in the path of the first wave, so shift will be 2 fringes upward.

Example: 17 In a *YDSE* fringes are observed by using light of wavelength 4800 Å, if a glass plate (μ = 1.5) is introduced in the path of one of the wave and another plates is introduced in the path of the (μ = 1.8) other wave. The central fringe takes the position of fifth bright fringe. The thickness of plate will be

(a) 8 *micron* (b) 80 *micron* (c) 0.8 *micron* (d) None of these

Solution: (a) Shift due to the first plate $x_1 = \frac{\beta}{\lambda}(\mu_1 - 1)t$ (Upward)

and shift due to the second $x_2 = \frac{\beta}{\lambda}(\mu_2 - 1)t$ (Downward)



Hence net shift = $x_2 - x_1 = \frac{\beta}{\lambda}(\mu_2 - \mu_1)t$

$\Rightarrow 5p = \frac{\beta}{\lambda}(1.8 - 1.5)t \;\Rightarrow t = \frac{5\lambda}{0.3} = \frac{5 \times 4800 \times 10^{-10}}{0.3} = 8 \times 10^{-6} m = 8\,micron$.

***Example*: 18** In young double slit experiment $\frac{d}{D} = 10^{-4}$ (d = distance between slits, D = distance of screen from the slits). At a point P on the screen resulting intensity is equal to the intensity due to individual slit I_0. Then the distance of point P from the central maxima is (λ = 6000 Å)

(a) 2 *mm* (b) 1 *mm* (c) 0.5 *mm* (d) 4 *mm*

Solution: (a) By using shift $I = 4I_0\cos^2(\phi/2) \Rightarrow I_0 = 4I_0\cos^2(\phi/2) \Rightarrow \cos(\phi/2) = \frac{1}{2}$ or $\frac{\phi}{2} = \frac{\pi}{3} \Rightarrow \phi = \frac{2\pi}{3}$

Also path difference $\Delta = \frac{xd}{D} = \frac{\lambda}{2\pi} \times \phi \Rightarrow x \times \left(\frac{d}{D}\right) = \frac{6000 \times 10^{-10}}{2\pi} \times \frac{2\pi}{3} \Rightarrow x = 2 \times 10^{-3} m = 2mm$.

***Example*: 19** Two identical radiators have a separation of $d = \lambda/4$, where λ is the wavelength of the waves emitted by either source. The initial phase difference between the sources is $\pi/4$. Then the intensity on the screen at a distance point situated at an angle $\theta = 30°$ from the radiators is (here I_0 is the intensity at that point due to one radiator)

(a) I_0 (b) $2I_0$ (c) $3I_0$ (d) $4I_0$

Solution: (a) Initial phase difference $\phi_0 = \frac{\pi}{4}$; Phase difference due to path difference $\phi' = \frac{2\pi}{\lambda}(\Delta)$

where $\Delta = d\sin\theta \Rightarrow \phi' = \frac{2\pi}{\lambda}(d\sin\theta) = \frac{2\pi}{\lambda} \times \frac{\lambda}{4}(\sin 30^o) = \frac{\pi}{4}$

Hence total phase difference $\phi = \phi_0 + \phi' = \frac{\phi}{4}$. By using $I = 4I_0\cos^2(\phi/2) = 4I_0\cos^2\left(\frac{\pi/2}{2}\right) = 2I_0$.

***Example*: 20** In *YDSE* a source of wavelength 6000 Å is used. The screen is placed 1 *m* from the slits. Fringes formed on the screen, are observed by a student sitting close to the slits. The student's eye can distinguish two neighbouring fringes. If they subtend an angle more than 1 minute of arc. What will be the maximum distance between the slits so that the fringes are clearly visible

(a) 2.06 *mm* (b) 2.06 *cm* (c) 2.06×10^{-3} *mm* (d) None of these

Solution: (a) According to given problem angular fringe width $\theta = \frac{\lambda}{d} \geq \frac{\pi}{180 \times 60}$ $\left[\text{As}\, 1' = \frac{\pi}{180 \times 60} rad\right]$

i.e. $d < \frac{6 \times 10^{-7} \times 180 \times 60}{\pi}$ *i.e.* $d < 2.06 \times 10^{-3} m \Rightarrow d_{max} = 2.06\,mm$

***Example*: 21** the maximum intensity in case of interference of n identical waves, each of intensity I_0, if the interference is (i) coherent and (ii) incoherent respectively are

(a) n^2I_0, nI_0 (b) nI_0, n^2I_0 (c) nI_0, I_0 (d) $n^2I_0, (n-1)I_0$

Solution: (a) In case of interference of two wave $I = I_1 + I_2 + 2\sqrt{I_1I_2}\cos\phi$

(i) In case of coherent interference ϕ does not vary with time and so I will be maximum when $\cos\phi = \max = 1$

i.e. $(I_{\max})_{co} = I_1 + I_2 + 2\sqrt{I_1 I_2} = (\sqrt{I_1} + \sqrt{I_2})^2$

So for n identical waves each of intensity I_0 $(I_{\max})_{co} = (\sqrt{I_0} + \sqrt{I_0} + ...)^2 = (n\sqrt{I_0})^2 = n^2 I_0$

(ii)In case of incoherent interference at a given point, ϕ varies randomly with time, so $(\cos\phi)_{av} = 0$ and hence $(I_R)_{Inco} = I_1 + I_2$

So in case of n identical waves $(I_R)_{Inco} = I_0 + I_0 + ... = nI_0$

***Example*: 22** The width of one of the two slits in a Young's double slit experiment is double of the other slit. Assuming that the amplitude of the light coming from a slit is proportional to the slit width. The ratio of the maximum to the minimum intensity in interference pattern will be

(a) $\frac{1}{a}$ (b) $\frac{9}{1}$ (c) $\frac{2}{1}$ (d) $\frac{1}{2}$

Solution: (b) $A_{\max} = 2A + A = 3A$ and $A_{\min} = 2A - A = A$. Also $\frac{I_{\max}}{I_{\min}} = \left(\frac{A_{\max}}{A_{\min}}\right)^2 = \left(\frac{3A}{A}\right)^2 = \frac{9}{1}$

***Example*: 23** A star is moving towards the earth with a speed of $4.5 \times 10^6 m/s$. If the true wavelength of a certain line in the spectrum received from the star is 5890 Å, its apparent wavelength will be about $[c = 3 \times 10^8 m/s]$

[MP PMT 1999]

(a) 5890 $\mathring{A}$ (b) 5978 $\mathring{A}$ (c) 5802 $\mathring{A}$ (d) 5896 $\mathring{A}$

Solution: (c) By using $\lambda' = \lambda\left(1 - \frac{v}{c}\right) \Rightarrow \lambda' = 5890\left(1 - \frac{4.5 \times 10^6}{3 \times 10^8}\right) = 5802\ \mathring{A}$.

***Example*: 24** Light coming from a star is observed to have a wavelength of 3737 Å, while its real wavelength is 3700 Å. The speed of the star relative to the earth is [Speed of light $= 3 \times 10^8 m/s$] **[MP PET 1997]**

(a) $3 \times 10^5 m/s$ (b) $3 \times 10^6 m/s$ (c) $3.7 \times 10^7 m/s$ (d) $3.7 \times 10^6 m/s$

Solution: (b) By using $\Delta\lambda = \lambda\frac{v}{c} \Rightarrow$ (3737-3700)= $3700 \times \frac{v}{3 \times 10^8} \Rightarrow v = 3 \times 10^6\ m/s$.

***Example*: 25** Light from the constellation Virgo is observed to increase in wavelength by 0.4%. With respect to Earth the constellation is

(a) Moving away with velocity $1.2 \times 10^6 m/s$ (b) Coming closer with velocity $1.2 \times 10^6 m/s$

(c) Moving away with velocity $4 \times 10^6 m/s$ (d) Coming closer with velocity $4 \times 10^6 m/s$

Solution: (a) By using $\frac{\Delta\lambda}{\lambda} = \frac{v}{c}$; where $\frac{\Delta\lambda}{\lambda} = \frac{0.4}{100}$ and $c = 3 \times 10^8$ *m/s* $\Rightarrow \frac{0.4}{100} = \frac{v}{3 \times 10^8} \Rightarrow v = 1.2 \times 10^6$ *m/s*

Since wavelength is increasing *i.e.* it is moving away.

Tricky example: 1

In *YDSE*, distance between the slits is 2×10^{-3} *m*, slits are illuminated by a light of wavelength 2000Å –9000 Å. In the field of view at a distance of 10^{-3} *m* from the central position which wavelength will be observe. Given distance between slits and screen is 2.5 *m*

(a) 40000 Å (b) 4500 Å (c) 5000 Å (d) 5500 Å

Solution : (b) $x = \frac{n\lambda D}{d} \Rightarrow \lambda = \frac{xd}{nD} = \frac{10^{-3} \times 2 \times 10^{-3}}{n \times 2.5} \Rightarrow \frac{8 \times 10^{-7}}{n} m = \frac{8000}{n} Å$

For n = 1, 2, 3....... λ = 8000 Å, 4000 Å, $\frac{8000}{3}$ Å.........

Hence only option (a) is correct.

Tricky example: 2

I is the intensity due to a source of light at any point P on the screen. If light reaches the point P via two different paths (a) direct (b) after reflection from a plane mirror then path difference between two paths is $3\lambda/2$, the intensity at P is

(a) I (b) Zero (c) $2I$ (d) $4I$

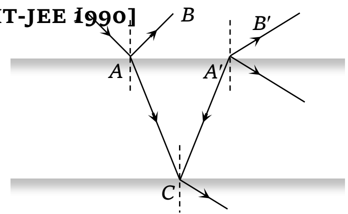
Solution : (d) Reflection of light from plane mirror gives additional path difference of $\lambda/2$ between two waves

$\therefore$ Total path difference $= \frac{3\lambda}{2} + \frac{\lambda}{2} = 2\lambda$

Which satisfies the condition of maxima. Resultant intensity $= (\sqrt{I} + \sqrt{I})^2 = 4I$.

Tricky example: 3

A ray of light of intensity I is incident on a parallel glass-slab at a point A as shown in figure. It undergoes partial reflection and refraction. At each reflection 25% of incident energy is reflected. The rays AB and $A'B'$ undergo interference. The ratio I_{max}/I_{min} is **[IIT-JEE 1990]**



(a) 4 : 1

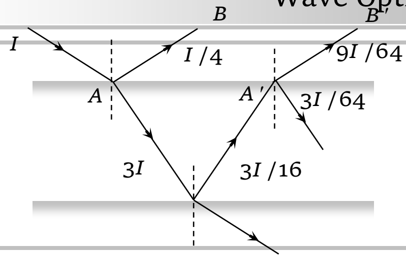
(b) 8 : 1

(c) 7 : 1

(d) 49 : 1

Solution : (d) From figure $I_1 = \frac{I}{4}$ and $I_2 = \frac{9I}{64} \Rightarrow \frac{I_2}{I_1} = \frac{9}{16}$

By using $\dfrac{I_{max}}{I_{min}} = \left(\dfrac{\sqrt{\dfrac{I_2}{I_1}}+1}{\sqrt{\dfrac{I_2}{I_1}}-1}\right) = \left(\dfrac{\sqrt{\dfrac{9}{16}}+1}{\sqrt{\dfrac{9}{16}}-1}\right) = \dfrac{49}{1}$



Fresnel's Biprism

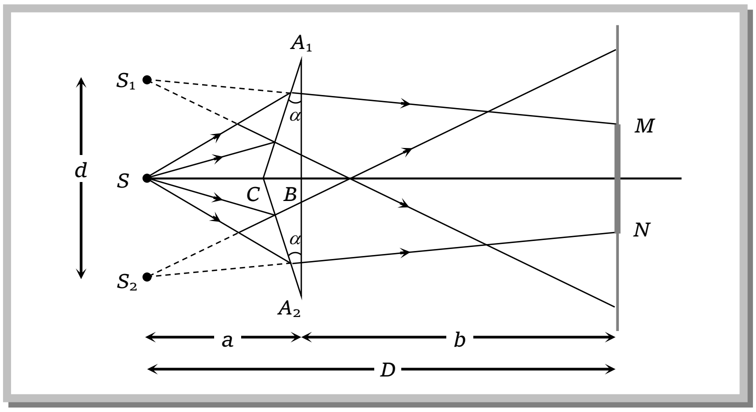
(1) It is an optical device of producing interference of light Fresnel's biprism is made by joining base to base two thin prism (A_1BC and A_2BC as shown in the figure) of very small angle or by grinding a thick glass plate.

(2) Acute angle of prism is about 1/2° and obtuse angle of prism is about 179°.

(3) When a monochromatic light source is kept in front of biprism two coherent virtual source S_1 and S_2 are produced.

(4) Interference fringes are found on the screen (in the MN region) placed behind the biprism interference fringes are formed in the limited region which can be observed with the help eye piece.

(5) Fringe width is measured by a micrometer attached to the eye piece. Fringes are of equal width and its value is $\beta = \dfrac{\lambda D}{d} \Rightarrow \lambda = \dfrac{\beta d}{D}$

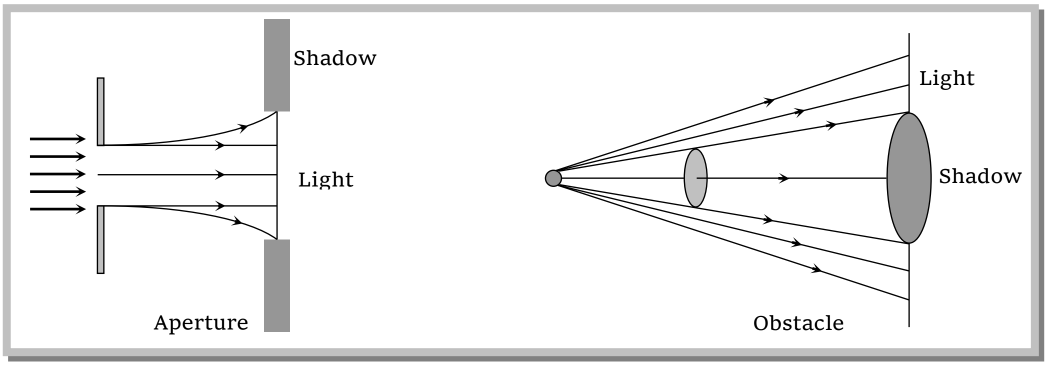


Let the separation between S_1 and S_2 be d and the distance of slits and the screen from the biprism be a and b respectively *i.e.* $D = (a + b)$. If angle of prism is α and refractive index is μ then $d = 2a(\mu - 1)\alpha$

$$\therefore \qquad \lambda = \frac{\beta[2a(\mu-1)\alpha]}{(a+b)} \quad \Rightarrow \quad \beta = \frac{(a+b)\lambda}{2a(\mu-1)\alpha}$$

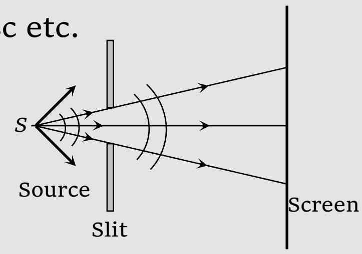
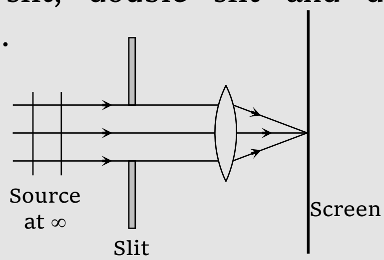
Diffraction of Light

It is the phenomenon of bending of light around the corners of an obstacle/aperture of the size of the wavelength of light.

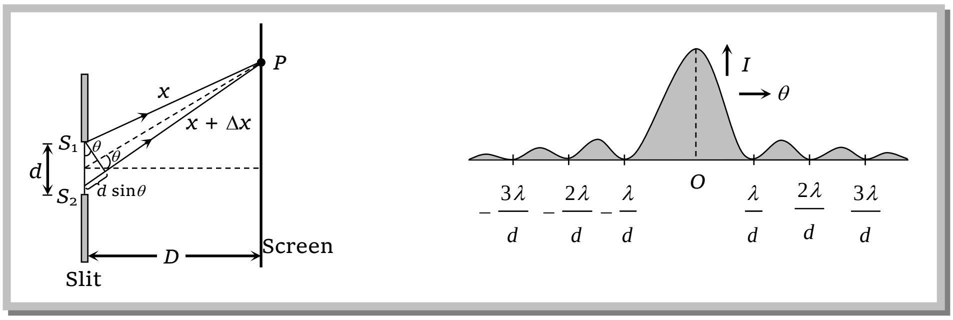


Note :
- Diffraction is the characteristic of all types of waves.
- Greater the wavelength of wave, higher will be it's degree of diffraction.
- Experimental study of diffraction was extended by Newton as well as Young. Most systematic study carried out by Huygens on the basis of wave theory.
- The minimum 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 $x = \frac{d^2}{4\lambda}$.

(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 $\beta_0 = \frac{2\lambda D}{d}$; and angular width $= \frac{2\lambda}{d}$

(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 $n = 1, 2, 3....$

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

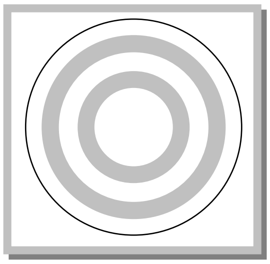
(iii) The secondary maxima occurs, where the path difference between the waves from the two ends of the aperture is given by $\Delta = (2n+1)\frac{\lambda}{2}$; where $n = 1, 2, 3....$

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

(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 $\beta = \frac{\lambda D}{d}$	All secondary fringes are of same width but the central maximum is of double the width $\beta_0 = 2\beta = 2\frac{\lambda D}{d}$
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 $x_{n(\text{Bright})} = \frac{n\lambda D}{d}$, $x_{n(\text{Dark})} = (2n-1)\frac{\lambda D}{d}$	Positions of nth secondary maxima and minima $x_{n(\text{Bright})} = (2n+1)\frac{\lambda D}{d}$, $x_{n(\text{Dark})} = \frac{n\lambda D}{d}$
Path difference for nth maxima $\Delta = n\lambda$	for nth secondary maxima $\Delta = (2n+1)\frac{\lambda}{2}$
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.

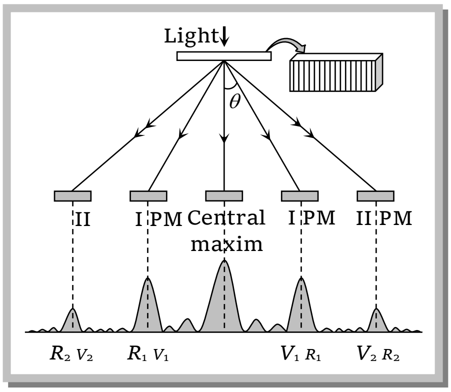


The angular half width of Airy disc $= \theta = \dfrac{1.22\lambda}{D}$ (where D = aperture of lens)

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.

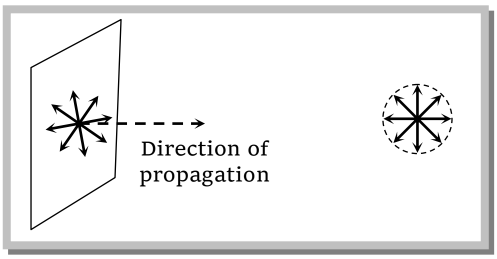


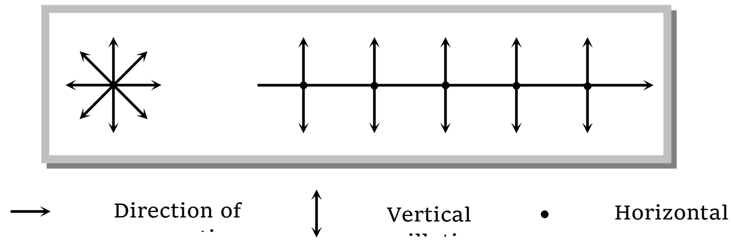
Polarisation of Light

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) **Polarised light**

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.

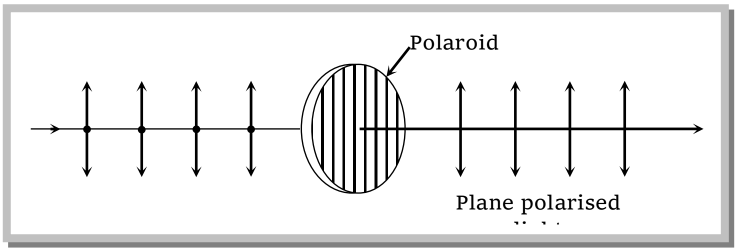
(iii) Light can be polarised by transmitting through certain crystals such as tourmaline or polaroids.

(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.

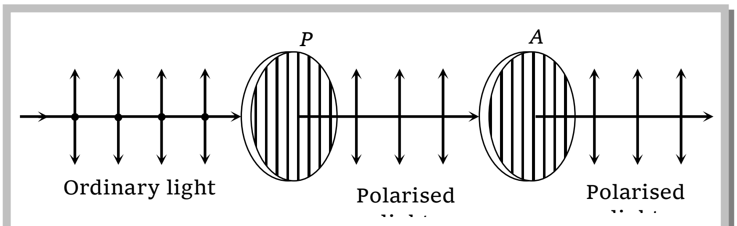
or

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

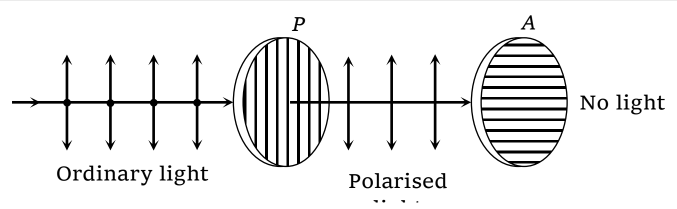


(i) Polaroids allow the light oscillations parallel to the transmission axis pass through them.

(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 analyser

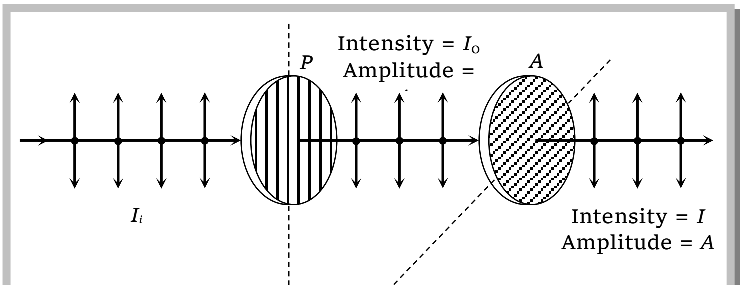


Transmission axis of the analyser is perpendicular to the polariser, hence no light passes through the analyser

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 $A^2 = A_0^2 \cos^2\theta \Rightarrow A = A_0 \cos\theta$

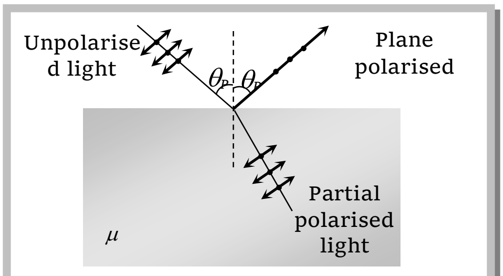
If $\theta = 0^o$, $I = I_0$, $A = A_0$, If $\theta = 45^o$, $I = \frac{I_0}{2}$, $A = \frac{A_0}{\sqrt{2}}$, If $\theta = 90^o$, $I = 0$, $A = 0$

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

So $I_0 = \frac{I_i}{2}$ *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 $I = \frac{I_i}{2}\cos^2\theta$

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

(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



Polarisation by

Also $\mu = \tan\theta_p$ Brewster's law

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

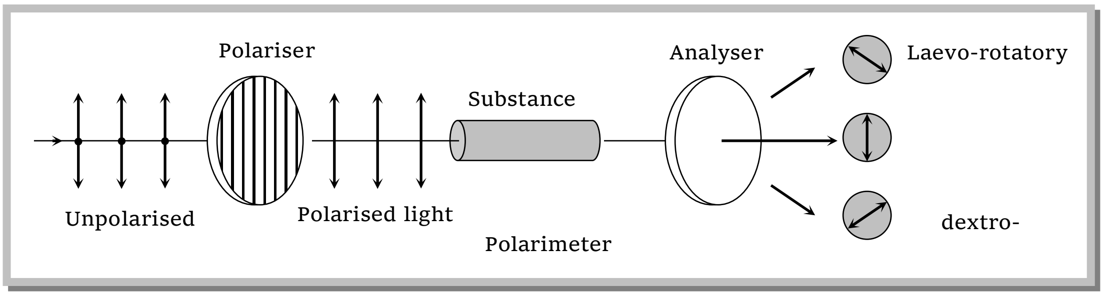
Both reflected and refracted rays becomes partially polarised

(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.* $[\alpha]_{t^oC}^{\lambda} = \frac{\theta}{L \times C}$ 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'.