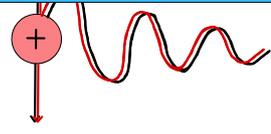




Wave Optics



Corpuscular model of light

Descartes gave the corpuscular (particle) model of light. The corpuscular model predicted that if ray of light on refraction, bends towards the normal, then the speed of light will be greater in the second medium.

Wave model of light

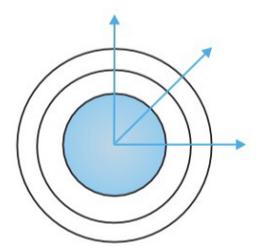
Christiaan Huygens put forward the wave theory of light. It predicted that on refraction if the ray of light bends towards the normal then, the speed of light will be lesser in the second medium.

- Note:**
1. Wavelength of light is very small as compared to dimensions of typical mirrors and lenses. Therefore, light can be assumed to travel approximately in a straight line.
 2. A ray is defined as the path of energy propagation in the limit of wavelength tending to zero.
 3. Light is a transverse electromagnetic wave.

Huygens' Principle (PYQ 2020, 2019, 2017, 2013)

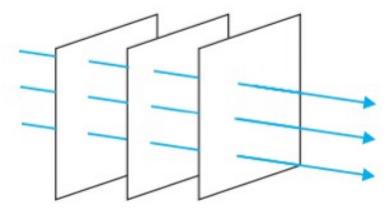
Wavefront- A locus of points, all of which oscillate in the same phase is called a wavefront. It is defined as a source of constant phase.

For e.g. When we drop a stone in water, waves spread out from the point of impact. At any instant, all the points on a circle where disturbance is maximum, oscillate in the same phase. This is because they are the same distance from the source.



- Point source-** spherical wavefront
- Line source-** cylindrical wavefront
- Plane source-** planar wavefront

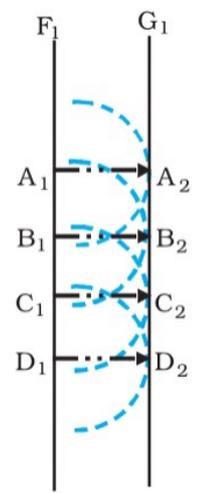
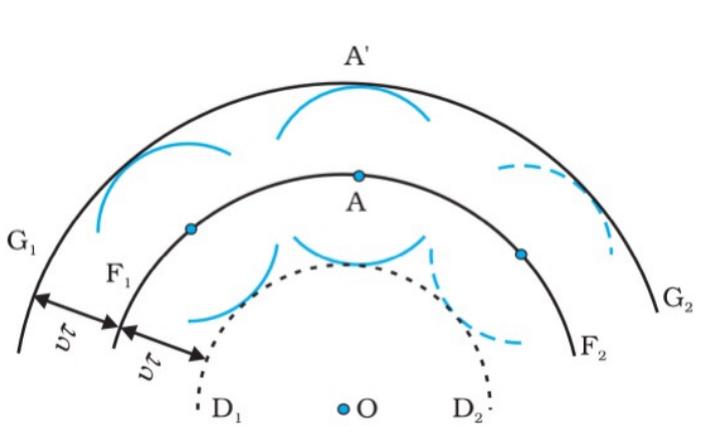
Speed of the wave- The speed with which the wavefront moves outwards from the source is called the speed of the wave. The energy of the wave travels in a direction perpendicular to the wave front.



Huygens' Principle-

'Each point of the wavefront is a source of a secondary disturbance and the wave emanating from these points spread out in all directions with the speed of the wave. These wavelets emanating from the wavefront are usually referred to as secondary wavelets and if we draw a common tangent to all these spheres, we obtain the new position of the wavefront at a later time.'

Thus, if we know the shape of the wavefront at say time $t=0$ and wish to determine its shape at a later time $t=\tau$, we draw spheres of radius $v\tau$ (where v is speed of the wave) from each point on the wavefront. We then draw a common tangent to all these spheres and we obtain the new wavefront at $t=\tau$



Anni Kaksha

Drawbacks of Huygens' Principle-

To explain the absence of a back wave, Huygens' argued that the amplitude of the wave is maximum in the forward direction and zero in the backward direction. But this explanation was not satisfactory.

Refraction and Reflection of Plane waves using Huygens' Principle

1. Refraction of plane wave (at a denser medium) (PYQ 2017)

Let PP' represent the surface separating medium 1 and 2 (medium 2 is denser). Let v_1 and v_2 be the speed of light in medium 1 and 2 respectively. We assume a plane wavefront AB propagating in the direction AA' incident on the interface at an angle i . Let τ be the time taken by wavefront to travel the distance BC.

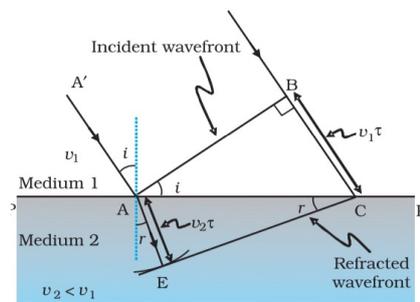
From the figure, we can write

$$\sin i = \frac{BC}{AC} = \frac{v_1 \tau}{AC}$$

$$\sin r = \frac{AE}{AC} = \frac{v_2 \tau}{AC}$$

Dividing both

$$\frac{\sin i}{\sin r} = \frac{v_1}{v_2}$$



From the above equation, we get that if $i > r$, i.e. the ray bends towards the normal, the speed of light in the second medium will be less than that in the first medium i.e. $v_1 > v_2$. Let c be speed of light in vacuum-

$$n_1 = \frac{c}{v_1} \quad \Bigg| \quad n_2 = \frac{c}{v_2}$$

They are known as refractive indices of medium 1 and 2 respectively. We can write-

$$n_1 \sin i = n_2 \sin r$$

This is called Snell's law of refraction. If λ_1 and λ_2 are the wavelengths of light in the first and second medium, and if in the fig. $BC = \lambda_1$, then, the distance AE will be equal to λ_2 , this is because if the crest has reached C from B in time τ , then the crest from A should also reach E in the same time (as they are oscillating in the same phase). Thus,

$$\frac{\lambda_1}{\lambda_2} = \frac{BC}{AE} = \frac{v_1}{v_2}$$

$$\frac{v_1}{\lambda_1} = \frac{v_2}{\lambda_2}$$

This implies that when a wave gets refracted into a denser medium-

1. Wavelength and speed of propagation decreases
2. Frequency remains the same

2. Refraction at a rarer medium (PYQ 2020, 2019, 2013)

Consider a light wave going from a denser medium to a rare medium. The ray bends away from the normal i.e. $r > i$. The speed of light in medium 1 is greater than that in medium 2 i.e. $v_1 > v_2$. However, we still have the following equation-

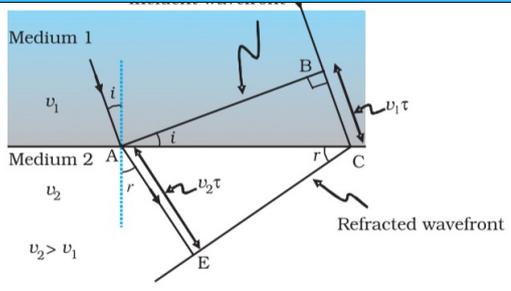
$$n_1 \sin i = n_2 \sin r$$

We define the angle i_c by the following equation-

$$\sin i_c = \frac{n_2}{n_1}$$

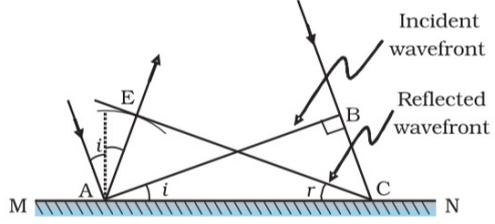
Thus, if $i = i_c$ then $\sin r = 1$ and $r = 90^\circ$. For $i > i_c$, there will be no refracted wave. The angle i_c is known as critical angle. For all angles of refractions greater than the critical angle, we will not have any refracted and the wave will undergo what is known as total internal reflection.

A. K. K.



3. Reflection of a wave by a plane surface (PYQ 2019)

Consider a plane wave AB incident at an angle i on a reflecting surface MN. If v represents the speed of the wave in the medium and if τ represents the time taken by the wavefront to advance from the point B to C then-



$$BC = v\tau$$

To draw the reflected wavefront, draw a sphere of radius $v\tau$ from A. let CE be the tangent plane drawn from the point C to this sphere-

$$AE = BC = v\tau$$

Consider -

$\triangle EAC$ & $\triangle BAC$

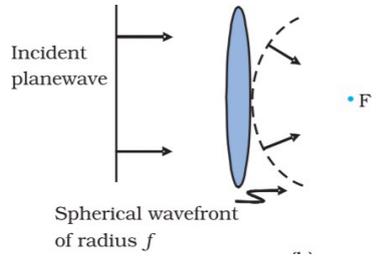
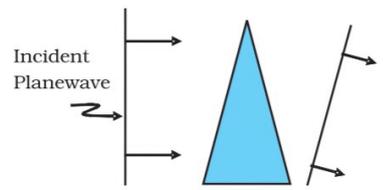
$$AE = BC$$

$$AC = AC$$

$$\angle AEC = \angle CBA = 90^\circ$$

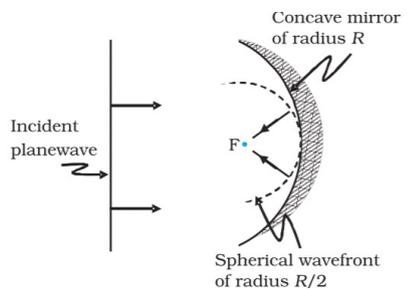
$$\triangle EAC \cong \triangle BAC$$

$$\Rightarrow i = r$$



4. Behavior of Prisms, lenses and mirrors

- a. Prism- since speed of light is less in glass, the lower portion of the wavefront which coming from the thickest part of the prism will get delayed as shown
- b. Convex lens- the center portion of the incoming wavefront has to pass through the thickest portion and gets delayed the most. Emerging wavefront has a depression at the center and therefore the wavefront becomes spherical and converges to the point F which is called the focus.
- c. Concave mirror- when a plane wave is incident on a concave mirror, on reflection we have a spherical wave which converges to the focal point F.



Note: The total time taken from a point on the object to the corresponding time on the image is the same, measured along any path. For e.g. when a convex lens focuses to form a real image, although the ray going through the center travels a shorter path, but because of the slower speed in the glass, the time is the same as for rays travelling near the edge of the lens.

A : Kaksha

The Doppler effect

When the source moves away from the observer, frequency as measured by the source will be smaller. This is known as Doppler effect. This is because if the source moves away from an observer, the wavefronts have to travel a greater distance to reach the observer and hence take a longer time and the time taken between the arrival of successive wavefronts is hence longer at the observer than at the source.

Red shift- The increase in wavelength due to doppler effect is called red shift since a wavelength towards the middle of the spectrum moves towards the red end of the spectrum.

Blue shift- If waves are received from an observer moving towards the observer, the apparent decrease in wavelength is referred to as blue shift.

For velocities very small as compared to the speed of light in vacuum (c), the fractional change in the frequency is given by –

$$\frac{\Delta v}{v} = - \frac{v_{radial}}{c}$$

Where v_{radial} is the component of source velocity along the line joining the source and the observer.

Sign convention- v is taken as +ve when the source approaches the observer and -ve when the source moves away from the observer

Coherent and Incoherent addition of waves

Coherent sources- Two sources having same wavelength, frequency and a constant phase difference are coherent in nature. Their amplitudes may be different.

Principle of Superposition- At a particular point in a medium, the net displacement produced due to a number of waves is the sum of displacements produced by each of the waves

Intensity of wave-

$$I = \frac{1}{2} \rho A^2 \omega^2 V \quad (V \text{ is velocity of wave and } \rho \text{ is density of the medium})$$

Therefore, for coherent waves-

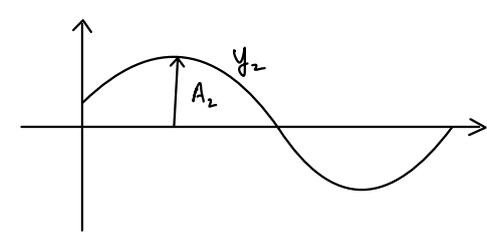
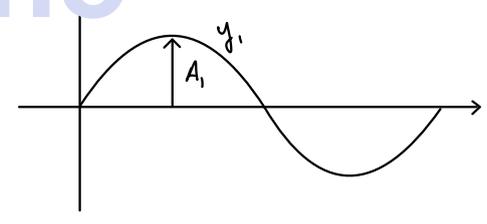
$$I \propto A^2$$

Let us consider the superposition of the following two waves. Let-

$$y_1 = A_1 \sin(kx - \omega t)$$

$$y_2 = A_2 \sin(kx - \omega t + \phi)$$

Therefore, the net displacement



$$y = y_1 + y_2$$

$$y = A_1 \sin(kx - \omega t) + A_2 \sin(kx - \omega t + \phi)$$

$$y = A_1 \sin(kx - \omega t) + A_2 \sin(kx - \omega t) \times \cos \phi + A_2 \cos(kx - \omega t) \times \sin \phi \quad (\because \sin(A+B) = \sin A \times \cos B + \cos A \times \sin B)$$

$$y = (A_1 + A_2 \cos \phi) \times \sin(kx - \omega t) + A_2 \sin \phi \times \cos(kx - \omega t)$$

Let- $A_1 + A_2 \cos \phi = R \cos \delta$; $A_2 \sin \phi = R \sin \delta$

Substituting in y

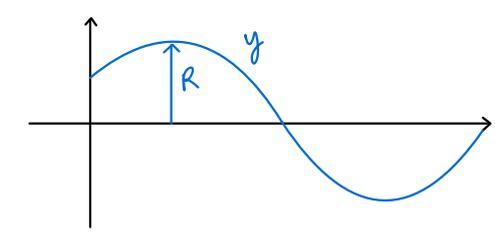
$$y = R \sin(kx - \omega t) \times \cos \delta + R \cos(kx - \omega t) \times \sin \delta$$

$$y = R \sin(kx - \omega t + \delta) \quad (\because \sin(A+B) = \sin A \times \cos B + \cos A \times \sin B)$$

Where-

$$R^2 \sin^2 \delta + R^2 \cos^2 \delta = (A_1 + A_2 \cos \phi)^2 + A_2^2 \sin^2 \phi$$

$$R^2 = A_1^2 + A_2^2 + 2A_1 A_2 \cos \phi$$



$$A_1 + A_2 \cos \phi$$

So we can say-

$$A^2 = A_1^2 + A_2^2 + 2A_1A_2 \cos \phi$$

$$\Rightarrow I = I_1 + I_2 + 2 \sqrt{I_1 I_2} \times \cos \phi \quad (\because I \propto A^2)$$

1. If the two sources are incoherent

If they are incoherent, the phase difference between them will be a function of time {f(t)}. So, we calculate the average intensity-

$$\langle I \rangle = \langle I_1 + I_2 + 2 \times \sqrt{I_1 I_2} \times \cos \phi \rangle$$

$$\langle I \rangle = I_1 + I_2 + 0$$

$$I = I_1 + I_2 \quad (\text{Since the phase difference will vary with time and we know average of cosine over a cycle is zero})$$

Therefore, the average intensity at a point will just be the arithmetic sum of the intensities of the two waves. For e.g. when two light bulbs light up a wall

2. If the sources are coherent (PYQ 2019)

The net intensity-

$$I = I_1 + I_2 + 2 \sqrt{I_1 I_2} \times \cos \phi$$

$$I = I_1 + I_2 + 2 \times \sqrt{I_1 I_2} \cdot \cos \left(\frac{2 \times \pi \cdot \Delta x}{\lambda} \right)$$

$$\therefore (\sqrt{I_1} - \sqrt{I_2})^2 \leq I \leq (\sqrt{I_1} + \sqrt{I_2})^2$$

Note: Consider two waves having phase difference $\Delta\phi$ and path difference Δx -

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

Where λ is the wavelength of the wave.

Interference

When two coherent waves superimpose in a medium, a redistribution of energy takes place in the medium. This phenomenon is called interference.

1. Constructive Interference

At the point where the two sources are vibrating in phase i.e. phase difference-

$$\cos \phi = 1$$

The waves are said to interfere constructively. So, we see-

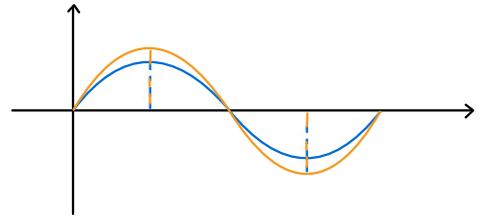
$$\phi = 0, \pm 2 \cdot \pi, \pm 4 \cdot \pi, \dots$$

$$\Rightarrow \Delta x = 0, \pm \lambda, \pm 2\lambda \dots \quad (\text{Refer to note above})$$

Generalising-

$$\phi = \pm 2n\pi$$

$$\Delta x = \pm n\lambda \quad (n = 0, 1, 2, 3, \dots \infty)$$



Also,

$$I = I_1 + I_2 + 2 \times \sqrt{I_1 I_2} \times (1)$$

$$I = (\sqrt{I_1} + \sqrt{I_2})^2$$

2. Destructive Interference

At the point where the two sources are vibrating out of phase i.e. phase difference-

$$\cos \phi = -1$$

The waves are said to interfere destructively. So, we see-

$$\phi = \pm \pi, \pm 3\pi, \pm 5\pi$$

$$\Rightarrow \Delta x = \pm \frac{\lambda}{2}, \pm \frac{3\lambda}{2}, \pm \frac{5\lambda}{2}$$

Generalising-

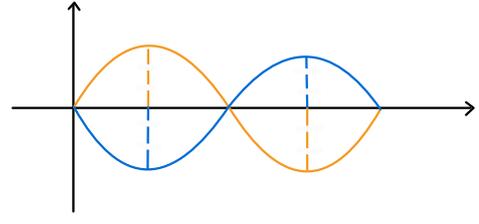
$$\phi = \pm (2n - 1) \times \pi \quad (n = 1, 2, 3 \dots \infty)$$

$$\Delta x = \pm (2n - 1) \times \frac{\lambda}{2}$$

OR

$$\phi = \pm (2n + 1) \times \pi \quad (n = 0, 1, 2, 3 \dots \infty)$$

$$\Delta x = \pm (2n + 1) \times \frac{\lambda}{2}$$



Also,

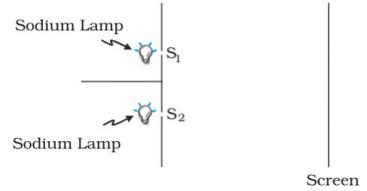
$$I = I_1 + I_2 + 2 \times \sqrt{I_1 I_2} \times (-1)$$

$$I = (\sqrt{I_1} - \sqrt{I_2})^2$$

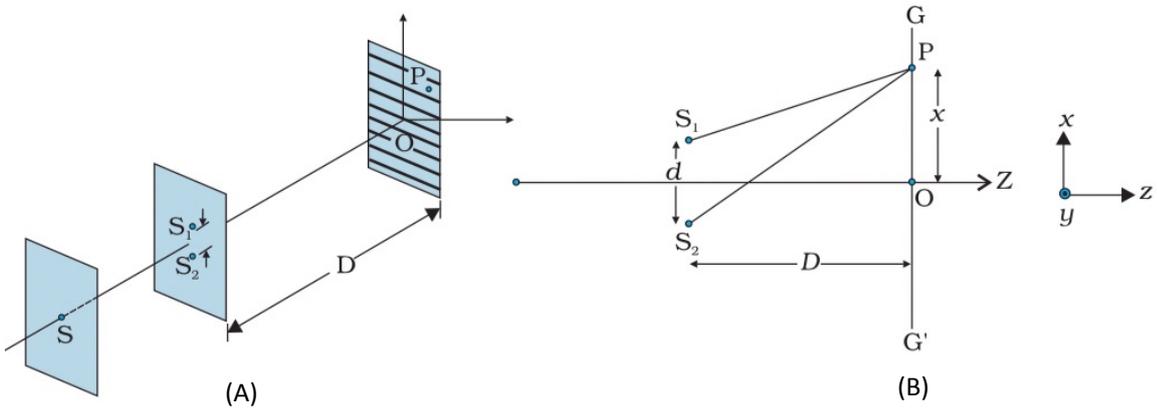
ATDB.uno

Young's Double Slit Experiment (YDSE) (PYQ 2020, 2018, 2016, 2015, 2014, 2011)

If we use two sodium lamps illuminating two pinholes, we will not observe any interference. This is because of the fact that light wave emitted from an ordinary source (like a lamp) undergoes abrupt phase changes. Thus, light waves coming out from two independent sources of light will not have any fixed phase relationship and would be incoherent.



So, to fix this problem, Thomas Young made two pinholes S₁ and S₂ very close to each other on an opaque screen which were lit by a common source S. The sources S₁ and S₂ behave like two coherent sources because light coming out of these sources is derived from the same original source and any abrupt phase change in S would manifest in exactly similar phase changes in S₁ and S₂. Therefore, the two sources will be locked in phase.



From the fig (b), let us calculate the path difference between S_1P and S_2P i.e. we need $S_1P - S_2P$. We can write-

$$(S_2P)^2 - (S_1P)^2 = \left[\left(x + \frac{d}{2} \right)^2 + D^2 \right] - \left[\left(x - \frac{d}{2} \right)^2 + D^2 \right]$$

$$(S_2P)^2 - (S_1P)^2 = 2 \cdot x \cdot d$$

Also,

$$(S_2P)^2 - (S_1P)^2 = (S_2P - S_1P) \cdot (S_2P + S_1P)$$

$$2x \cdot d = \Delta x (2S_2P) \quad (\text{Where } \Delta x \text{ is path difference})$$

For $D \gg d$, $S_1P = S_2P = D$. Therefore, substituting this we get-

$$x = \frac{D}{d} \cdot \Delta x$$

Case 1: Constructive Interference-

For constructive interference we know,

$$\Delta x = \pm n\lambda$$

$$\Rightarrow x = \frac{D}{d} \times (\pm n\lambda)$$

Case 2: Destructive interference:

ATDB.uno

For destructive interference we know-

$$\Delta x = \pm (2n - 1) \times \frac{\lambda}{2}$$

$$\Rightarrow x = \frac{D}{d} \times \left(\pm (2n - 1) \times \frac{\lambda}{2} \right)$$

Thus, white and dark bands appear on the screen and such bands are called fringes. Fringes are equi-spaced.

Fringe width (β)

It is defined as the separation between two successive maxima or minima i.e. -

$$\beta = \frac{D}{d} \times (n\lambda) - \frac{D}{d} \times (n - 1)\lambda$$

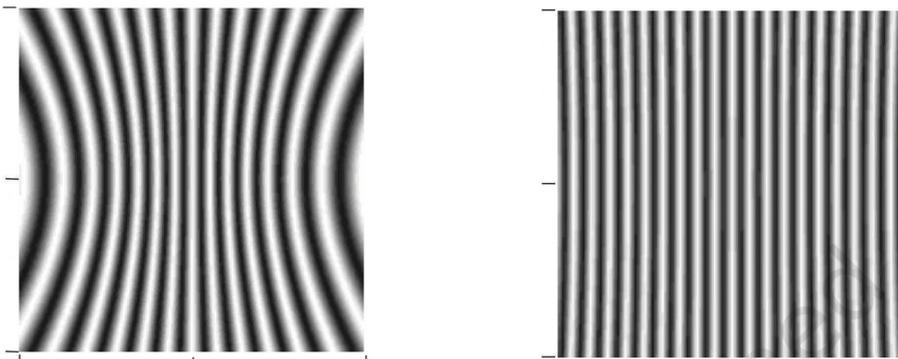
$$\beta = \frac{\lambda D}{d}$$

Angular width

It is defined as the angle subtended by a fringe width at one of the slits

$$\frac{\beta}{D} = \frac{\lambda}{d}$$

Note: 1. The fringe pattern is a hyperbola. But if the distance D is very large as compared to the fringe width, the fringes will be nearly straight lines.



2. If source S is on perpendicular bisector, then the central fringe also occurs at O , also on the perpendicular bisector. If S is shifted to a point S' at angle ϕ then, the central fringe occurs at a point O' at an angle $-\phi$ i.e. it is shifted by the same angle on the other side of the bisector
3. If we had slits instead of point sources, each pair of points would have produced straight line fringes resulting in straight line fringes with increased intensities.

Important PYQs



Ques: What is the effect on interference fringes in Young's Double slit experiment due to the following operations? Justify your answers-

1. Screen is moved away from the plane of the slits
2. The separation between the slits is increased
3. Source slit is moved closer to plane of double slits

Ans: 1. Angular separation of the fringes remains constant. The actual separation of the slits increases in proportion to the distance of the screen from the plane of the slits.

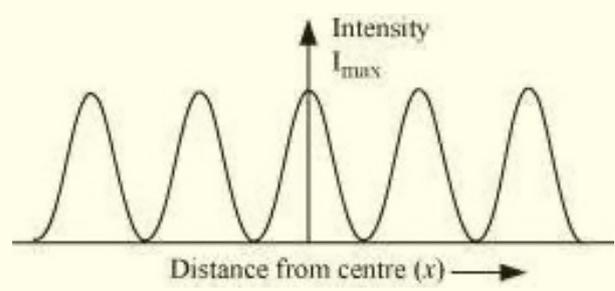
2. The separation of the fringes and the angular separation decreases

3. Let s be the size of the source and S its distance from the plane of the two slits. For interference fringes to be seen, the condition $s/S < \lambda/d$ should be satisfied; otherwise, interference patterns produced by different parts of the source overlap and no fringes are seen. Thus, as S decreases (i.e., the source slit is brought closer), the interference pattern gets less and less sharp, and when the source is brought too close for this condition to be valid, the fringes disappear. Till this happens, the fringe separation remains fixed.



Ques: In YDSE, draw a graph showing variation of intensity pattern of interference against position x on the screen (PYQ 2016) [2M]

Ans:



Ques: In YDSE, the wavelength of light used is 600 nm and the angular width formed on the screen is 0.1°. find spacing between the two slits. (PYQ 2015) [2M]

Ans: First convert degrees into radians-

$$0.1^\circ = 0.00175^c$$

ATQ, $\frac{\lambda}{d} = 0.00175$

$$d = \frac{600 \times 10^{-9}}{0.00175}$$

$$d = 3.42 \times 10^{-4} m$$

Ques: Two independent sources of monochromatic light can never produce a sustained pattern of interference. Explain

Ans: If we use two sodium lamps illuminating two pinholes, we will not observe any interference. This is because of the fact that light wave emitted from a ordinary source like a lamp undergoes abrupt phase changes. Thus, light waves coming out from two independent sources of light will not have any fixed phase relationship and would be incoherent.

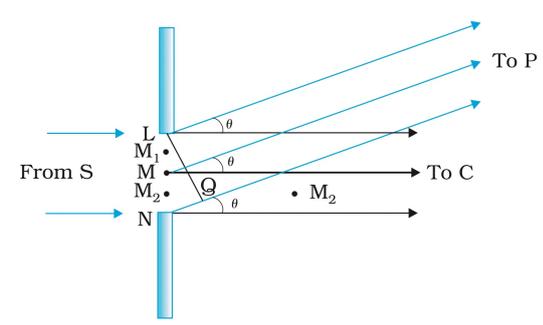
Diffraction (2019, 2018, 2015, 2011, 2010)

It's the phenomenon of spreading of a wave when it encounters an obstacle of size comparable to its wavelength

Note: Diffraction is a general characteristic exhibited by all types of waves, be it sound waves, water waves, light waves, or matter waves. i.e. Diffraction is a sure test of wave nature.

The Single Slit-

When a narrow slit is illuminated by a monochromatic source of light, a broad pattern with a bright central region is seen. On both sides there are light and dark regions the intensity of which becomes weaker as we move away from the centre.



Consider the following figure with a slit LN of width a on which a parallel beam of light is falling. The midpoint of the slit is M and the light gets diffracted onto a screen.

Consider a point P on the screen. Point P will be a minima if the waves from L and M have a phase difference of π at P-

$$\Delta x = \frac{a}{2} \times \sin \theta = \frac{\lambda}{2}$$

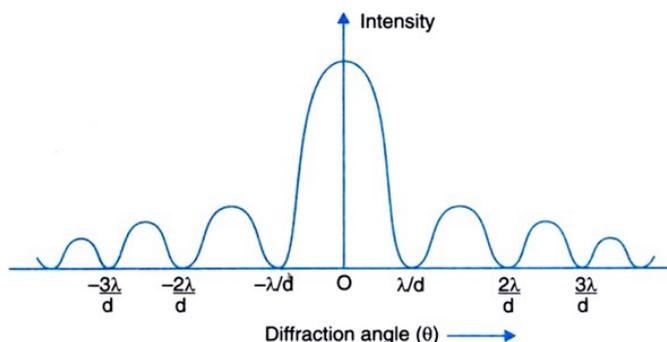
$$\Rightarrow a \sin \theta = \lambda$$

In this manner, the angular position of the minima can be computed by-

$$a \sin \theta = \pm n \lambda \quad (n = 1, 2, 3, \dots \infty)$$

Similarly, maxima can be computed by-

$$a \sin \theta = \pm \left(\frac{n+1}{2} \right) \lambda \quad (n = 1, 2, 3, \dots \infty)$$



Difference between Interference pattern and single slit diffraction pattern

Interference pattern	Single slit diffraction pattern
1. The interference pattern has a number of equally spaced bright and dark bands.	1. The diffraction pattern has a central bright maximum which is twice as wide as the other maxima. The intensity falls as we go to successive maxima away from the centre, on either side.
2. We calculate the interference pattern by superposing two waves originating from the two narrow slits	2. The diffraction pattern is a superposition of a continuous family of waves originating from each point on a single slit.
3. For double slit at an angle of λ/a , we get a maximum (not a null) for two narrow slits separated by a distance a .	3. For a single slit of width a , the first null of the interference pattern occurs at an angle of λ/a

Important PYQs

Ques: In diffraction due to a single slit experiment, the aperture of the slit is 3mm. if monochromatic light of wavelength 620 nm is incident normally on the slit, then find the distance between the first order minima and 3rd order maxima on one side of the screen. The separation between the slit and screen is 1.5 m **(PYQ 2019) [2M]**

Ans: Position of the first order minima-

$$\frac{y_1}{D} = \frac{\lambda}{a}$$

$$y_1 = \frac{620 \times 10^{-9} \times 1.5}{3 \times 10^{-3}}$$

$$y_1 = 3.1 \times 10^{-4} m$$

Position of third maxima-

$$\frac{y_2}{D} = \left(\frac{n+1}{2} \right) \times \frac{\lambda}{a}$$

$$y_2 = 6.2 \times 10^{-4} m$$

Separation-

$$y_2 - y_1 = 6.2 \times 10^{-4} - 3.1 \times 10^{-4}$$

$$y_2 - y_1 = 3.1 \times 10^{-4} m$$

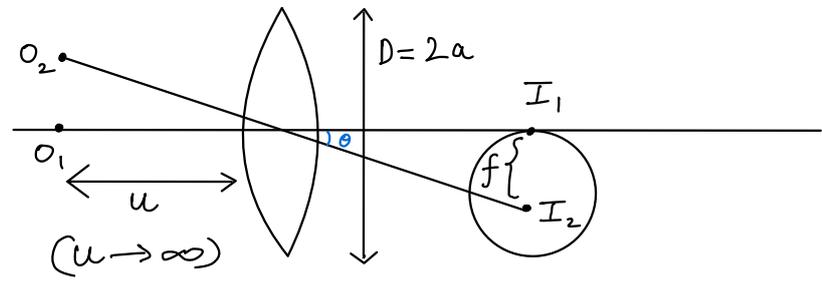
Resolving Power of Optical Instruments

Limit of resolution-

1. Limit of resolution is the ability to clearly distinguish two different objects
2. Limit of resolution is controlled by diffraction

Resolution of Telescope-

Consider a parallel beam of light falling on a convex lens of diameter 2a. Due to diffraction, the light spreads and gets focused to spot of finite area instead of being focused at a point. So, the pattern of diffraction on the focal plane would consist of a central bright surrounded by bright and dark rings. So-



$$\theta = \frac{1.22\lambda}{2a}$$

Where θ is called angular resolution or limit of resolution.

Resolving power of telescope (R.P)-

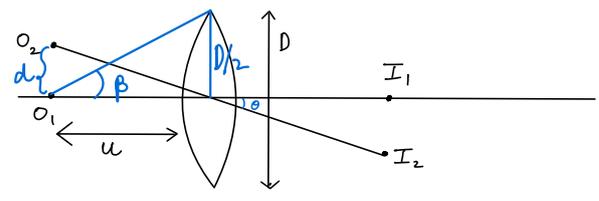
It is defined as –

$$R \cdot P = \frac{1}{\theta} = \frac{D}{1.22\lambda}$$

This implies that telescope will have better resolving power if a is large. It is for this reason that for better resolution, a telescope must have large diameter of objective .

Resolving Power of Microscope-

Consider the objective of a microscope of diameter D. Let O_1 and O_2 be two objects that need to be magnified. Let d be the minimum distance between the objects for which they can be resolved i.e. at distances shorter than this, they will be seen as one. From previous discussion of the telescope we know that-



$$\theta = \frac{d}{u} = \frac{1.22\lambda}{D} \quad \text{--- ①}$$

Also,

$$\sin \beta \approx \tan \beta \approx \frac{D}{2u} \quad \text{--- ②}$$

From 1,2

$$d = \frac{1.22\lambda}{\sin \beta}$$

Resolving power of microscope (R.P) can be defined as-

$$R \cdot P = \frac{1}{d} = \frac{2 \times \sin \beta}{1.22\lambda}$$

If a medium of refractive index n is introduced between the object and objective then –

$$R \cdot P = \frac{2n \sin \beta}{1.22\lambda}$$

Where the product $n \sin\theta$ is called the **numerical aperture**.

Note: 1. Oil immersion Objective- The resolving power of the microscope can be increased by choosing a medium of a high refractive index. usually an oil having refractive index close to that of the objective glass is used. This is called an oil immersion objective

2. A telescope produces images of far objects nearer to our eye whereas the microscope magnifies and produces large images of objects near to us. Therefore, a telescope resolves whereas a microscope magnifies.

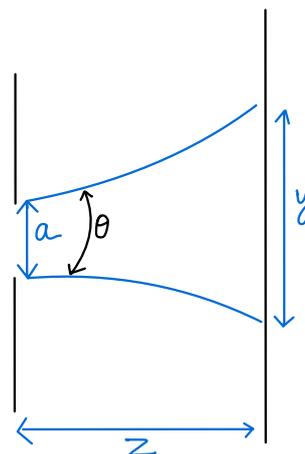
Validity of Ray Optics ★

An aperture (i.e., slit or hole) of size a , illuminated by a parallel beam sends diffracted light into an angle of approximately $\approx \lambda/a$. This is the angular size of the bright central maximum. In travelling a distance z , the diffracted beam therefore, acquires a width $y = z\lambda/a$ due to diffraction.

When the size of this spreading (y) becomes comparable to the slit width a , ray optics is no longer valid. So, we equate y with a which gives us the distance beyond which the divergence of the beam becomes significant i.e. ray optics ceases to be valid

$$z = \frac{a^2}{\lambda}$$

This distance is called Fresnel distance (Z_F)



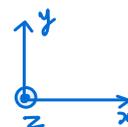
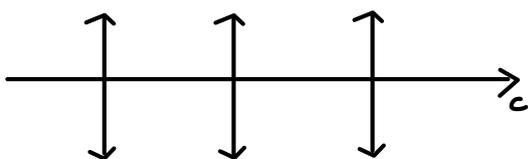
Polarization (PYQ 2018, 2017, 2015, 2011, 2010) ★

- 1. Transverse wave-** When displacement is at right angles to the direction of propagation of the wave it is called a transverse wave.
- 2. Unpolarised wave-** If plane of vibration of wave randomly changes in very short intervals of time, the wave is said to be unpolarised
- 3. Polarised wave-** When displacement is only in a single direction, the wave is said to be polarised
- 4. Linearly polarised wave-** When all particle of a polarised wave move on straight line, it is said to be linearly polarised
- 5. Plane polarised wave-** If the vibrations remain confined to one plane, the wave is said to be plane polarised.

Polarization is defined therefore as the phenomenon of confining the vibrations of a wave (light wave here), in a desired plane.

Note: Only transverse waves can be polarized i.e. polarization is a sure test of transverse nature.

e.g. Sound waves cannot be polarized (as they are longitudinal) but Light waves are transverse waves where **E**, **B** and **v** are all mutually perpendicular. Therefore, if a light wave travels in x direction, the electric field will oscillate in y - z plane



Plane of vibration- Plane containing direction of vibration and direction of propagation (e.g. x - y plane in fig above)

Plane of polarization- Plane containing direction of propagation perpendicular to direction of vibration (e.g. x - z plane in fig above)

Important PYQs

Ques: Which of the following can be polarized a) Heat waves b) Sound waves. Justify **(PYQ 2013) [1M]**

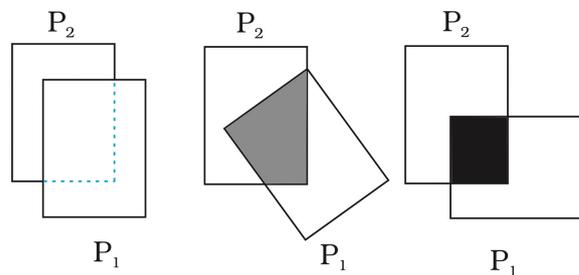
Ans: We know that only transverse waves can be polarized and since heat waves (IR waves) are EM waves which are transverse in nature and sound waves are longitudinal, only heat waves can be polarized.

Methods of polarization

1. Polaroids (2018, 2015)

Polaroids are thin plastic sheets which contain long chain molecules aligned in a particular direction. The electric vectors of the light wave along the direction of the aligned molecules get absorbed on passing through a polaroid. Thus, if an unpolarized light is incident on such a polaroid then the light will get linearly polarized with electric vector oscillating along direction perpendicular to the aligned molecules; this direction is called the pass axis of the polaroid.

Consider the following polaroids-



If unpolarized light is passed through polaroid P_1 intensity of the incident light is reduced by half. Rotating P_1 has no effect on intensity of transmitted beam and it remains constant. But if another polaroid P_2 is placed before P_1 , rotating P_2 has no effect but rotating P_1 has a dramatic effect on light coming from P_2 . This can be understood from the following law-

Malus's Law

If plane polarized light is incident on a polaroid, then intensity of transmitted light varies as-

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

Where θ is the angle that pass axis of P_2 makes with that of P_1 and I_0 is intensity of incident wave and I is intensity of transmitted wave

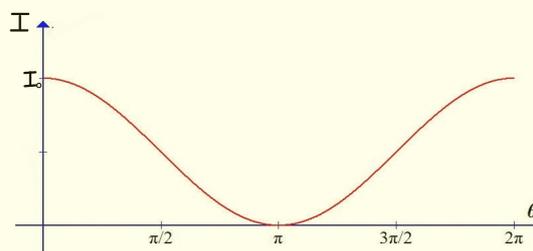
Uses of polaroids

- Used to control intensities in sunglasses and window panes
- Used in cameras and 3D movie cameras

Important PYQs

Ques: If plane polarized light is passed through a polaroid, show graphically the intensity of transmitted light as a function of the angle of rotation of the polaroid in one complete rotation **(PYQ 2018) [2M]**

Ans: $I = I_0 \cos^2 \theta$



Ques: Find expression for intensity of transmitted light when a polaroid sheet is rotated between two crossed polaroids. In which position is the intensity of transmitted light maximum? (PYQ 2015) [2M]

Ans: Let intensity of incoming unpolarized light be I_0 and let it pass through the first polaroid P_1 . So, we know that when unpolarized light is passed through a polaroid, the intensity becomes half. Therefore, the intensity I_1 -

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

Now let the angle between P_1 and the second polaroid P_2 be θ . So, the intensity of transmitted light I_2 will be-

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

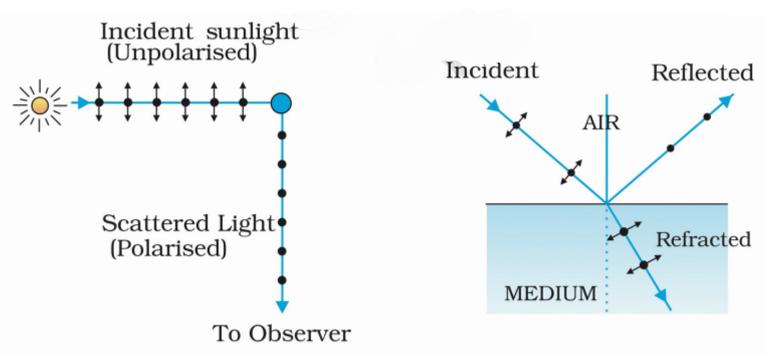
Now, finally light will pass through polaroid P_3 . Since P_1 and P_3 are crossed i.e. angle between them is 90° , and the angle between P_1 and P_2 is θ , the angle between P_2 and P_3 will be $90 - \theta$. Therefore, intensity of transmitted light I -

$$I_3 = I_2 \cos^2(90 - \theta) = \frac{I_0}{2} \cdot \cos^2 \theta \cdot \sin^2 \theta$$

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

2. Polarization by scattering (PYQ 2017)

Scattering is a process in which an atom or molecule radiates light in all possible directions. The radiated light in the direction perpendicular to the direction of incidence is completely polarized. The radiated light in all other directions is partially polarized



3. Polarization by reflection (PYQ 2017, 2016, 2014, 2010)

When unpolarized light is incident on the boundary between two transparent media, the reflected light is polarized with its electric field vector perpendicular to the plane of incidence when the refracted and reflected rays are perpendicular to each other i.e. -

When the reflected and refracted rays are perpendicular to each other, the reflected light is completely polarized. This is known as **Brewster's Law**. The angle of incidence for which reflected ray is completely polarized is called **Brewster's angle/ Polarizing angle**. Mathematically-

$$\mu = \frac{\sin i_B}{\sin r} = \frac{\sin i_B}{\sin(\frac{\pi}{2} - i_B)}$$

$$\mu = \frac{\sin i_B}{\cos i_B} = \tan i_B$$

Important PYQs

Ques: Find Brewster's angle for air-glass interface when the refractive index for glass is 1.5? (PYQ 2017) [1M]

$$\begin{aligned} \text{Ans: } \mu &= \tan i_B & i_B &= \tan^{-1}(1.5) \\ 1.5 &= \tan i_B & i_B &= 0.983 \end{aligned}$$

Ques: Brewster's angle for a transparent medium is different for different colors. Explain why (PYQ 2016) [1M]

Ans: We know that Brewster's angle for a transparent medium of refractive index μ is given by $\tan^{-1}(\mu)$ and since the value of μ for a transparent is different for different colors of light (i.e. depends on wavelength), the value of Brewster's angle also varies with change in color of light.

Definitions and Derivations as PYQs

Ques: Define wavefront of a travelling wave. Using Huygens' principle derive the law of refraction at plane interface when light passes from a denser medium to a rarer medium. (PYQ 2020, 2019, 2017, 2013) [2M]

Ques: Define wavefront of a travelling wave and using Huygens' principle derive the law of reflection (PYQ 2019) [3M]

Ques: Describe any two characteristic features which distinguish between the phenomena of diffraction and interference. Derive the expression for intensity at a point of the interference pattern observed in YDSE (PYQ 2019, 2018, 2016) [3M]

Ques: Draw a graph showing intensity distribution of fringes due to diffraction at single slit. (PYQ 2018) [1M]

Ques: When unpolarized light of intensity I_0 is passed through a polaroid, what is the intensity of transmitted light? Does it depend on the angle of rotation of polaroid? Justify your answer (PYQ 2018) [2M]

Ques: How is linearly polarized light obtained by the process of scattering? (PYQ 2017) [1M]

Ques: State Brewster's Law (PYQ 2016) [1M]

Ques: In YDSE deduce the condition for a) constructive and b) destructive interference at a point on the screen (PYQ 2016) [2M]

Ques: Light waves each of amplitude a and frequency ω coming from two coherent sources superpose at a point. If displacement due to these waves is given by $y_1 = a \cos(\omega t)$ and $y_2 = a \cos(\omega t + \phi)$, then find the expression for intensity at a point (ϕ is the phase difference) (PYQ 2014) [3M]

Ques: A beam of unpolarized light is incident on air-glass interface. Show using a ray diagram that the reflected light is completely polarized when $\mu = \tan(i_B)$ where i_B is called the Brewster's angle. (PYQ 2014, 2010) [1M]



A. K. W.