Revision Notes

Class - 12 Physics

Chapter 10 – Wave Optics

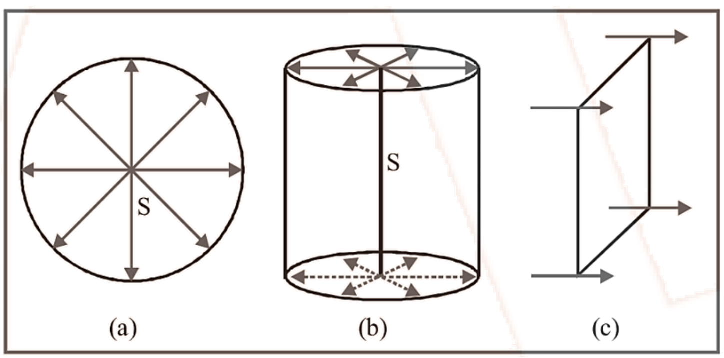
1. WAVE FRONT

A light source is a point which emits disturbance in all directions. In a homogeneous medium, the disturbance reaches all those particles of the medium in phase, which are located at the same distance from the source of light and hence at all the time, every particles must be vibrating in phase with each other. The locus of all the particles of medium, which at any instant are vibrating in the same phase, is called the wave front.

Depending upon the shape of the source of light, wave front can be the following types:

1.1 Spherical wave front

A point source of light produces spherical wave front. This is because, the locus of every points, which are equidistant from the point source, is a sphere figure (a).



1.2 Cylindrical wave front

If the light source is linear (such as a slit), it produces a cylindrical wave front. Here, every points, which are equidistant from the linear source, lie on the surface of a cylinder figure (b).

1.3 Plane wave front

A wave front will appear plane if small part of a spherical or a cylindrical wave front I originating from a distant source. So it is called a plane wave front figure (c).

1.4 Ray of light

The path along which light travels is known as a ray of light. If we draw an arrow normal to the wave front and which points in the direction of propagation of disturbance represents a ray of light. In a ray diagram, thick arrows represent the rays of light.

It is also called as the wave normal because the ray of light is normal to the wave front.

Key points

If we take any two points on a wave front, the phase difference between them will be zero.

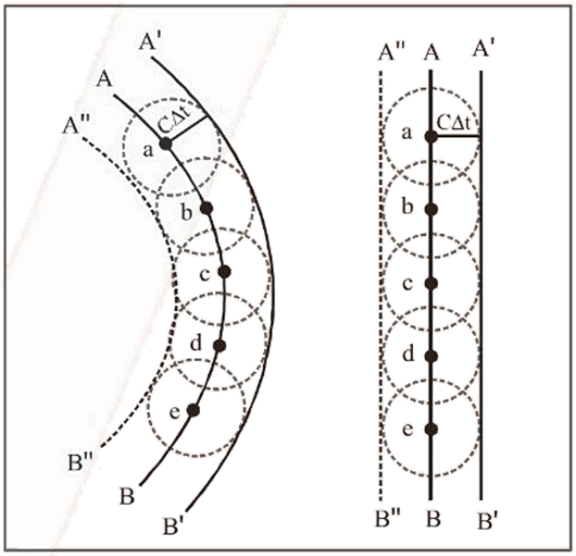
2. HUYGENS'S PRINCIPLE

Huygens's principle is a geometrical construction, which can be used to obtain new position of a wave front at a later time from its given position at any instant. Or we can quote that this principle gives a method gives an idea about how light spreads out in the medium.

It is developed on the following assumptions:

1. All the points on a given or primary wave front acts as a source of secondary wavelets, which sends out disturbance in all directions in a similar manner as the primary light source.
2. The new position of the wave front at any instant (called secondary wave front) is the envelope of the secondary wavelets at that instant.

These two assumptions are known as Huygens principle or Huygens' construction.



Key points

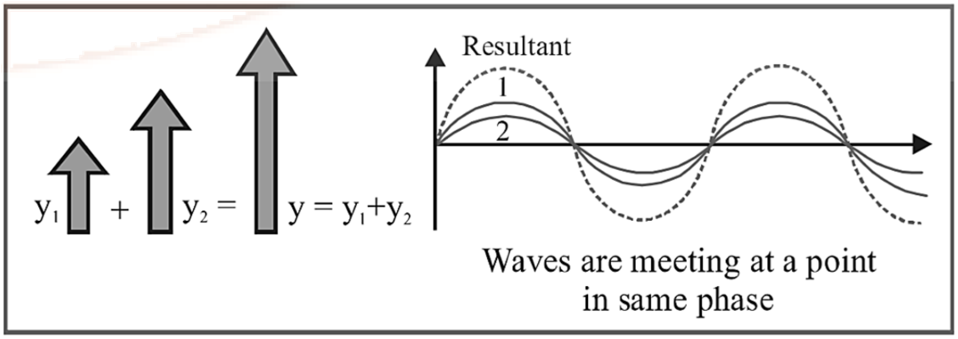
Huygens principle is simply a geometrical construction to find the position of wave front at a later time.

3. PRINCIPLE OF SUPER POSITION

If two or more than two waves superimpose 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 $\vec{y}=\vec{y_1}+\vec{y_2}$

3.1 Graphical view

i.



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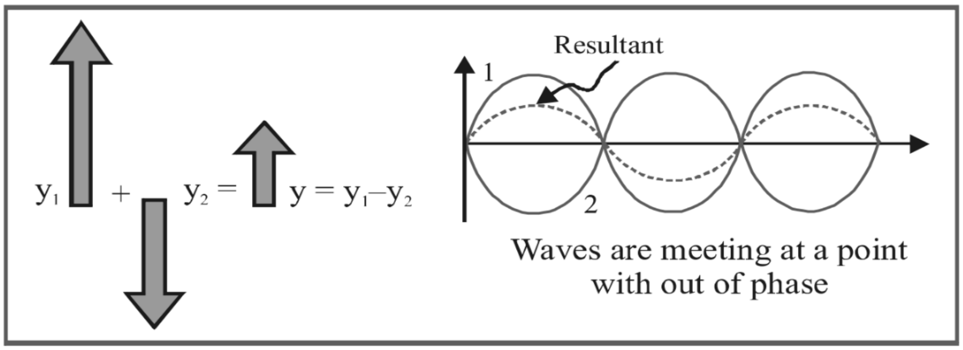


3.2 Phase/Phase difference/Path difference/Time difference

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

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

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

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

3.3 Resultant amplitude and intensity

If 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, $\phi =$ 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 $y_2 = a_2 \sin(\omega t + \phi)$, Phase difference between them is 90^o. So resultant amplitude $A = \sqrt{a_1^2 + a_2^2}$

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

$$I \text{-} I_1 + I_2 + 2\sqrt{I_1 I_2}\cos\phi$$

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

3.4 Coherent sources

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

4. INTERFERENCE OF LIGHT

If intensity of light at some points is maximum while at some other point intensity is minimum due to the simultaneous superposition of two waves of exactly same frequency (coming from two coherent sources) travels in a medium and in the same direction, this phenomenon is called Interference of light.

4.1 Types of Interference

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

4.2 Resultant intensity due to two identical waves 4

The resultant intensity for two coherent sources is given by

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

For identical source $I_1 = I_2 = I_0$

$$\Rightarrow I=I_0+I_0+2\sqrt{I_0I_0}\cos\phi=4I_0\cos^2\frac{\phi}{2}$$

$$\left[1+\cos\theta=2\cos^2\frac{\theta}{2}\right]$$

Note:

- Redistribution of energy takes place in the form of maxima and minima in interference
- 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:

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

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

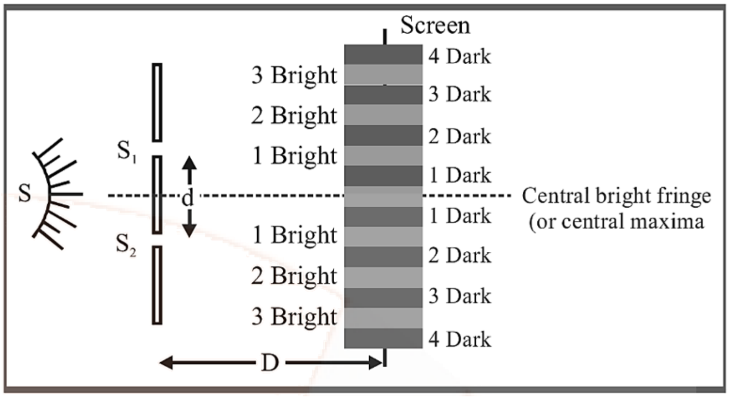
5. YOUNG'S DOUBLE SLIT EXPERIMENT (YDSE)

An interference pattern is obtained on the screen when monochromatic light (single wavelength) falls on two narrow slits S_1 and S_2 which are very close together acts as two coherent sources, and when waves coming from these two sources superimposes on each other. Alternate bright and dark bands obtained on the screen in this experiment. These bands are called Fringes.

$d =$ Distance between slits.

$D =$ Distance between slits and screen

= Wavelength of monochromatic light emitted from source.



1) At central position $\phi = 0^{o}$ or $\Delta = 0$. So, Central fringe will be always bright.

2) The fringe pattern formed by a slit will be brighter than that due to a point.

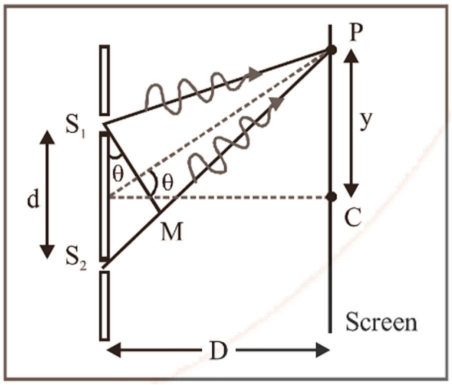
3) The minima will not be complete dark if the slit widths are unequal. So, uniform illumination occurs for very large width.

4) No interference pattern is observed on the screen if one slit is illuminated with red light and the other is illuminated with blue light.

5) The central fringe will be dark instead of bright if the two coherent sources consist of object and its reflected image.

5.1 Path difference

Path difference between the interfering waves meeting at a point P on the screen is given by $x = \frac{yd}{D} = d\sin\theta$ where x is the position of point P from central maxima.



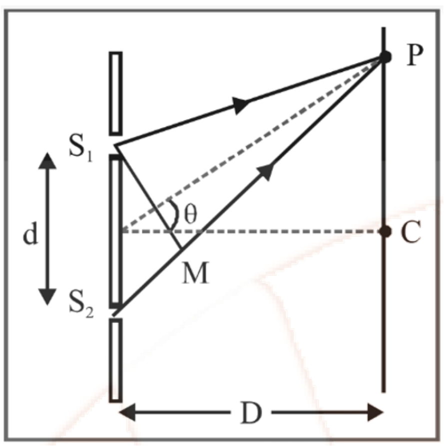
For maxima at P : $x = n\lambda$

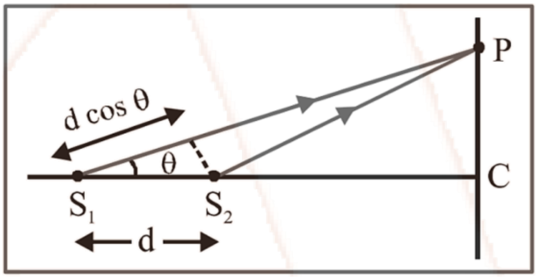
Where $n = 0, \pm 1, \pm 2, ...$

And for minima at P : $x = \frac{(2n-1)\lambda}{2}$

Where $n = 0, \pm 1, \pm 2, ...$

Note: If the slits are horizontal path difference is $d\cos\theta$, so as θ increases, x decreases. But if the slits are vertical, the path difference (x) is $d\sin\theta$, so as θ increases, Δ also increases.





5.2 More about fringe

(i) Every fringes will have equal width. Width of one fringe is $\beta = \dfrac{\lambda D}{d}$ and angular fringe width $\theta = \dfrac{\lambda}{d}$

(ii) If the YDSE setup is taken in one medium then changes into another, so β changes. E.g. in water $\lambda_w = \dfrac{\lambda_a}{\mu_w} \Rightarrow \beta_w = \dfrac{\beta_a}{\mu_w} = \dfrac{3}{4}\beta_a$

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

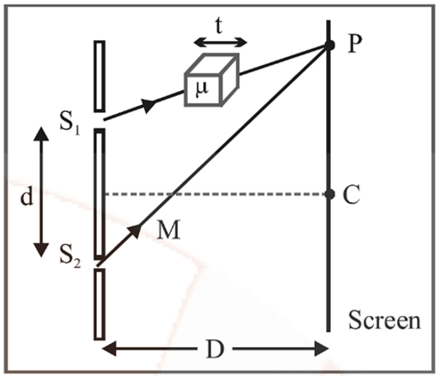
(iv) Position of n^{th} bright fringe from central maxima $x_n = \dfrac{n\lambda D}{d} = n\beta; n = 0, 1, 2, ..$

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

(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 $n_1\lambda_1 = n_2\lambda_2$

5.3 Shifting of fringe pattern in YDSE

The fringe pattern will get shifted if a transparent thin film of mica or glass is placed in the path of one of the waves. If this film is placed in the path of upper wave, the pattern shifts upward and if the film is placed in the path of lower wave, the pattern will shift downward.



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

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

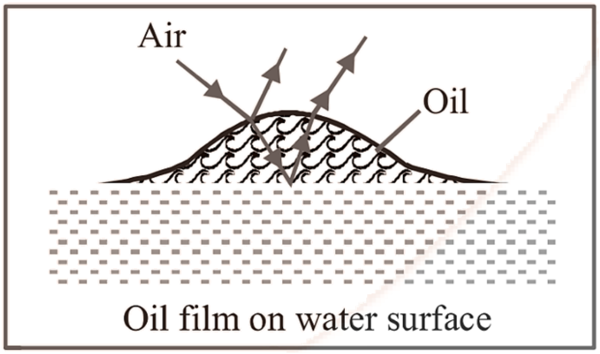
$\Rightarrow$If the shift is equivalent to n fringes, then $n=\frac{(\mu\text{-}1)t}{\lambda}$ or $t=\frac{n\lambda}{(\mu\text{-}1)}$

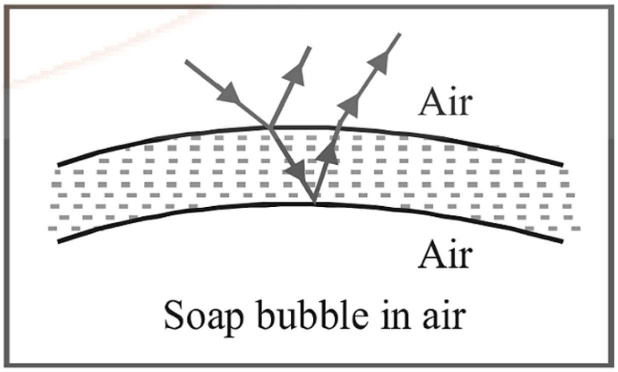
$\Rightarrow$Fringe shift is independent of the order of fringe (i.e shift of zero order maxima = shift of n^{th} order maxima)

$\Rightarrow$Also, the shift is independent of wavelength.

6. ILLUSTRATIONS OF INTERFERENCE

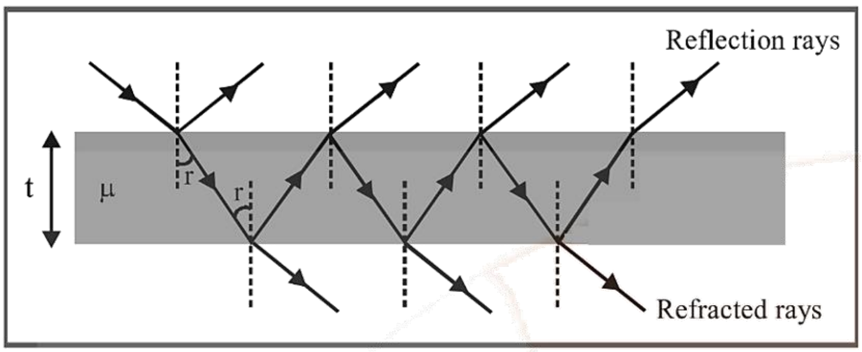
Interference effects are commonly observed in thin films when their thickness is comparable to wavelength of incident light (If it is too thin as compared to wavelength of light it appears dark and if it's too thick, this will return in uniform illumination of film). Thin layer of oil on water surface and soap bubbles shows various colours in white light due to interference of waves reflected from the two surfaces of the film.





6.1 Thin films

In case of thin films, interference occur between the waves reflected from its two surfaces and waves refracted through it.



Interference in reflected light	Interference in refracted light
Condition for constructive interference (maximum intensity)	Condition for constructive interference (maximum intensity)

$\Delta=2\mu t\cos r=(2n\pm1)\frac{\lambda}{2}$ For normal incidence $r=0$ So $2\mu t=(2n\pm1)\frac{\lambda}{2}$	$\Delta=2\mu t\cos r=(2n)\frac{\lambda}{2}$ For normal incident $2\mu t=n\lambda$
Condition for destructive interference (minimum intensity) $\Delta=2\mu t\cos r=(2n)\frac{\lambda}{2}$ For normal incidence $2\mu t=n\lambda$	Condition for destructive interference (minimum intensity) $\Delta=2\mu t\cos r=(2n\pm1)\frac{\lambda}{2}$ For normal incidence $2\mu t=(2n\pm1)\frac{\lambda}{2}$

Note: For interference in visible light, the thickness of the film must be in the order of 10,000A°

7. DOPPLER'S EFFECT IN LIGHT

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

According to special theory of relativity

$$\frac{v'}{v}=\frac{1\pm v/c}{\sqrt{1-v^2/c^2}}$$

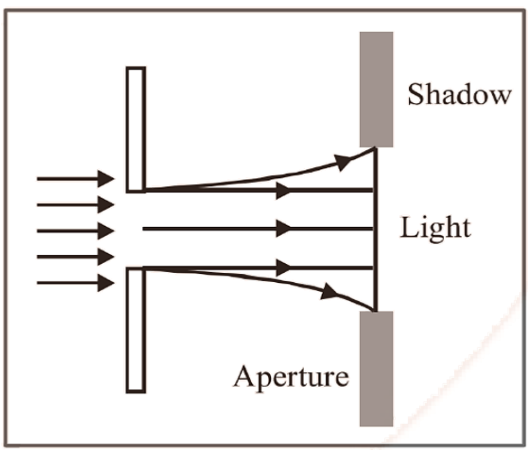
If $v=$ actual frequency, $v'=$ apparent frequency, $v=$ speed of source with respect to stationary observer, $c=$ speed of light.

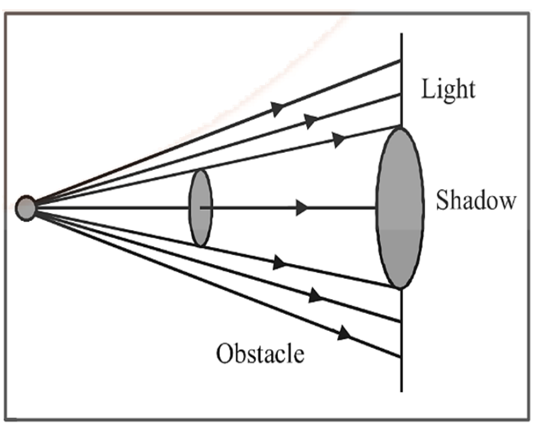
Source of light moves towards the stationary observer $(v<<c)$	**Source of light moves away from the stationary observer** $(v<<c)$
Apparent frequency $v'=v\left(1+\frac{v}{c}\right)$ and Apparent wavelength $\lambda'=\lambda\left(1-\frac{v}{c}\right)$	Apparent frequency $v'=v\left(1-\frac{v}{c}\right)$ and Apparent wavelength $\lambda'=\lambda\left(1+\frac{v}{c}\right)$

Doppler's shift: If apparent wavelength < actual wavelength, spectrum of the radiation from the source of light shifts towards the red end of the spectrum. This is called Red shift Doppler's shift $\Delta\lambda=\lambda\frac{v}{c}$	(ii)Doppler's shift: If apparent wavelength > actual wavelength, spectrum of the radiation from the source of light shifts towards the violet end of spectrum. This is called Violet shift Doppler's shift $\Delta\lambda=\lambda.\frac{v}{c}$

8. DIFFRACTION OF LIGHT

The phenomenon of light bending around the corners of an obstacle/aperture whose size is comparable to the size of the wavelength of light.

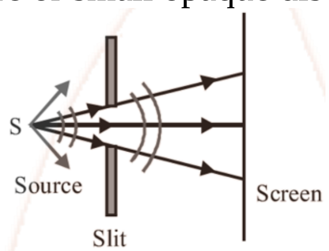


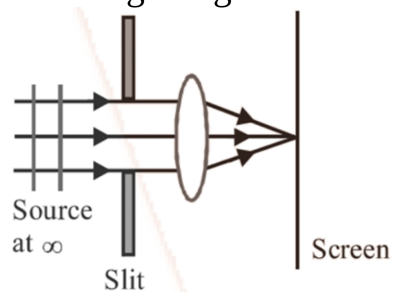


8.1 Types of diffraction

The diffraction phenomenon of light is divided into two types

<table>
<tr><th>Fresnel diffraction</th><th>Fraunhofer diffraction</th></tr>
<tr><td>In Fresnel’s diffraction, either source or screen or both are at finite distance from the diffracting device (obstacle or aperture).

Common examples:
Diffraction at a straight edge narrow wire or small opaque disc etc.

</td><td>In this case both source and screen are effectively at infinite distance from the diffracting device.

Common examples:
Diffraction at single slit, double slit and diffraction grating.

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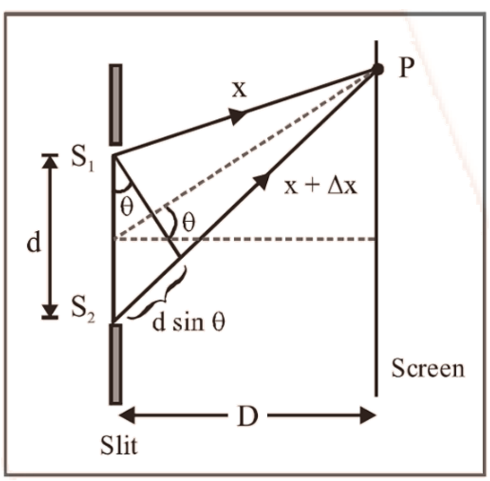
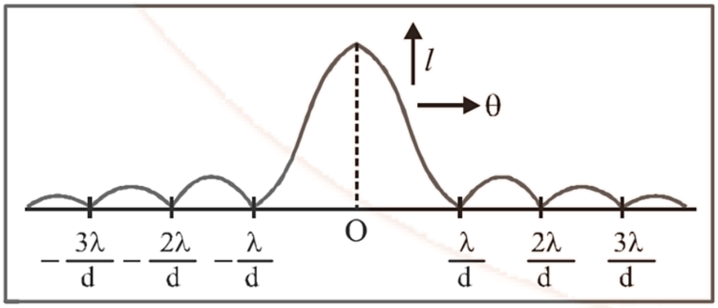
8.2 Diffraction of light at a single slit

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 $\beta_o = \frac{2\lambda D}{d}$ and angular width $= \frac{2\lambda}{d}$

(ii) 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. $d\sin\theta = n\lambda$ as the minima occurs at a point on either side of the central maxima.

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

(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

$$n=1,2,3,...\text{i.e. } d\sin\theta = (2n+1)\frac{\lambda}{2} \Rightarrow \sin\theta = \frac{(2n+1)\lambda}{2d}$$

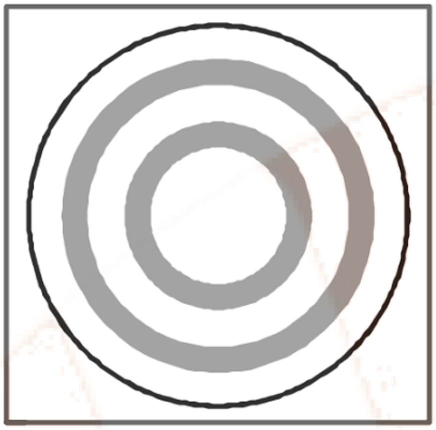
8.3 Comparison between interference and diffraction

Interference	Diffraction
Produced by the superimposition of waves from two coherent sources.	Produced by the superposition of wavelets from different parts of same wave front. (single coherent source)

All fringes are of the same width $\beta=\frac{\lambda D}{d}$	All secondary fringes are of same width but the central maxima has double the width $\beta_o=2\beta=2\frac{\lambda D}{d}$
All fringes have equal intensity	Intensity decreases as the order of maximum increases.
Intensity of all minimum may be zero. Positions of n^{th} maxima and minima. $X_{n(bright)}=\frac{n\lambda D}{d}$ $X_{n(Dark)}=(2n-1)\frac{\lambda D}{d}$	Intensity of minima is not zero. Positions of n^{th} secondary maxima and $X_{n(Bright)}=(2n+1)\frac{\lambda D}{d}$ $X_{n(Dark)}=\frac{n\lambda D}{d}$
Path difference for n^{th} maxima $\Delta=n\lambda$	For n^{th} secondary maxima $\Delta=(2n+1)\frac{\lambda}{2}$
Path difference for n^{th} minima $\Delta=(2n-1)\lambda$	Path difference for n^{th} minima $\Delta=n\lambda$

8.4 Diffraction and optical instruments

Objective lens of instrument like telescope or microscope etc. acts like a circular aperture. By diffraction of light at the circular aperture, a converging lens doesn't form a point image of an object rather it produces a brighter disc surrounded by alternate dark and bright concentric rings known as Airy disc.



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

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

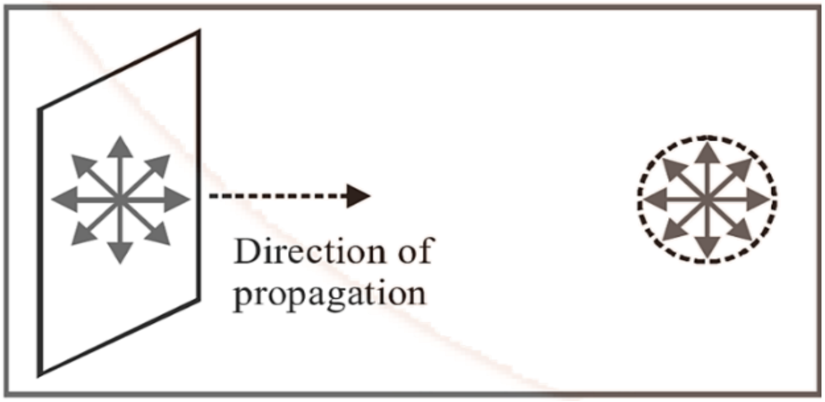
Note: Diffraction of light limits the ability of optical instruments to form clear images of objects when they are close to each other.

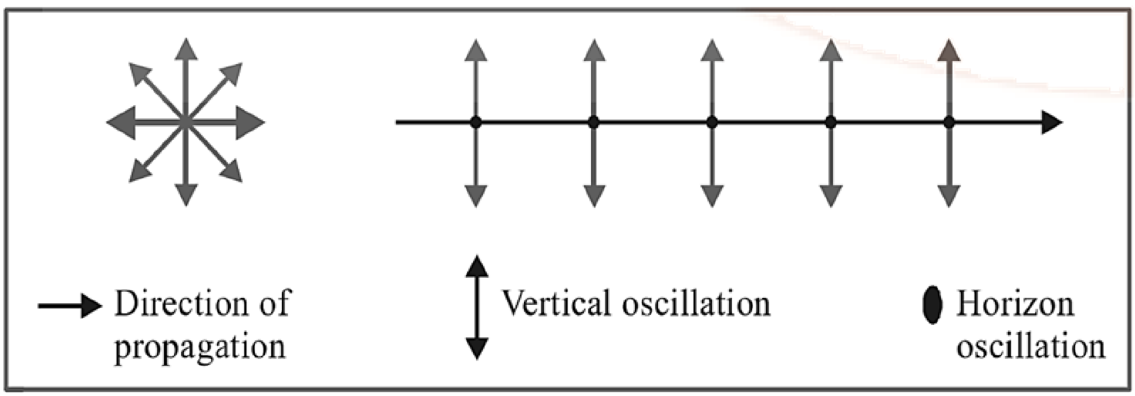
9. POLARIZATION OF LIGHT

Light travel as transverse EM waves. While comparing to magnitude of magnetic field, the magnitude of electric field is much larger. We generally describe light as electric field oscillations.

9.1 Unpolarized light

Light with electric field oscillations in every directions in the plane perpendicular to the propagation of it is called Unpolarised light. The oscillation of light is divided into horizontal and vertical component.





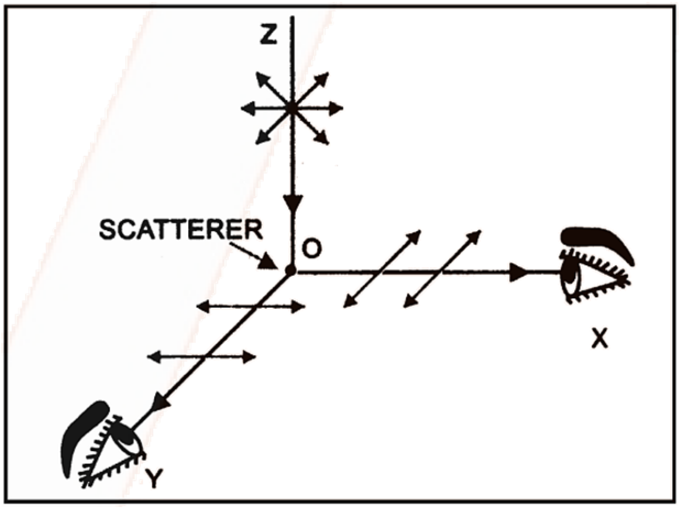
9.2 Polarized light

Polarized or plane polarized light is the light with oscillations only in one plane is.

1. Plane of oscillation is the plane in which oscillation occurs in the polarized light.
2. Plane of polarization is the plane perpendicular to the plane of oscillation.
3. By transmitting through certain crystals such as tourmaline or Polaroid light can be polarized.

9. 3 Polarization by Scattering

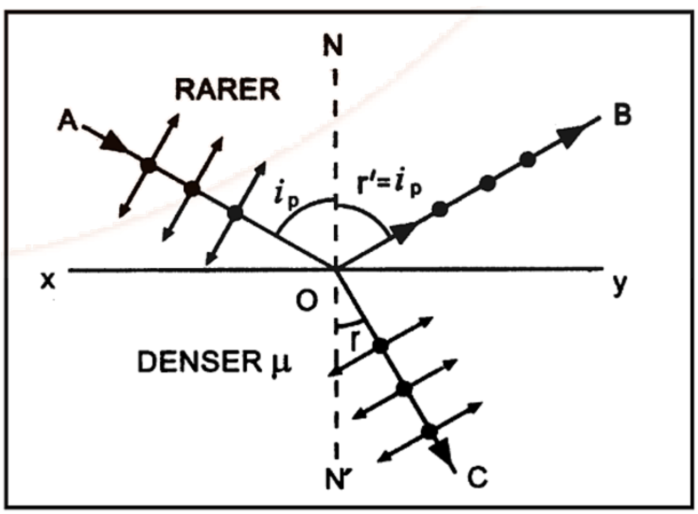
If a beam of white light is passed through a medium having particles with size comparable to the order of wavelength of light, then the beam will get scattered. This scattered light propagates in a direction perpendicular to the direction of incidence, and it will be plane polarized (as detected by the analyzer). This is called polarization by scattering.



9.4 Polarization of Light by Reflection

If unpolarized light is reflected using a surface, the reflected light can be obtained as completely polarised, partially polarized or unpolarized. The nature of reflected light depends on the angle of incidence.

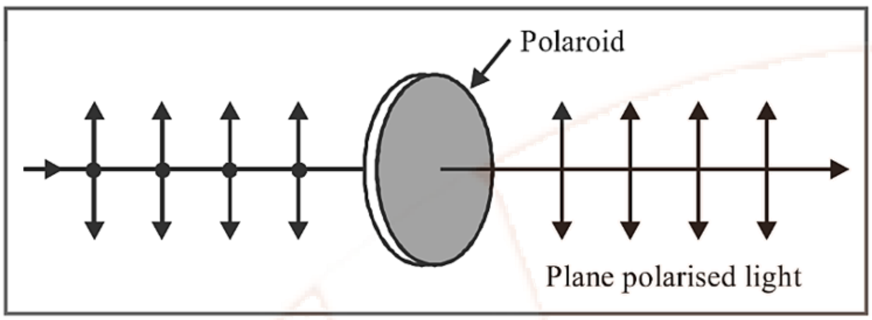
Polarizing angle or Brewster's angle $\left(i_p\right)$ is the angle of incidence when the reflected light is completely plane polarized.



9.5 Polaroid

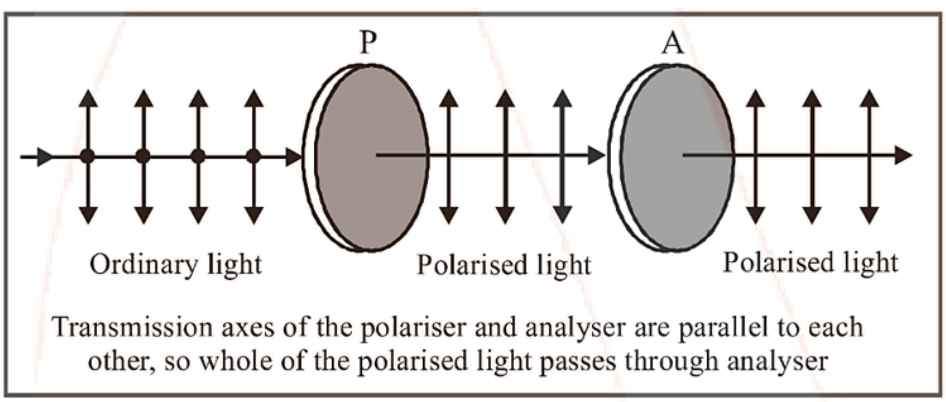
The device used to produce the plane polarised light is known as a Polaroid. It is based on the principle of selective absorption. Also, it is more effective than the tourmaline crystal.

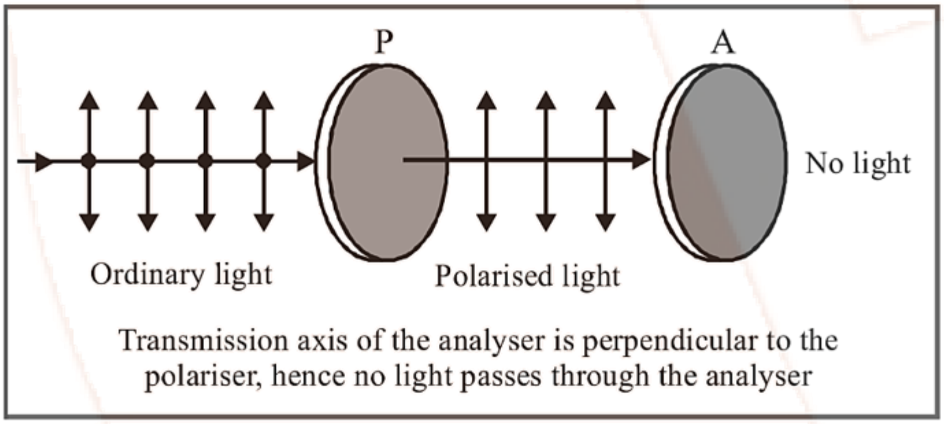
It can also be described as a thin film of ultramicroscopic crystals of quinine idosulphate which has its optic axis parallel to each other.



(i) A Polaroid only allows light oscillations which are parallel to the transmission axis to pass through them.

(ii) Polarizer is the crystal or Polaroid on which unpolarised light is incident. Crystal or polaroid on which polarised light is incident is called analyzer.



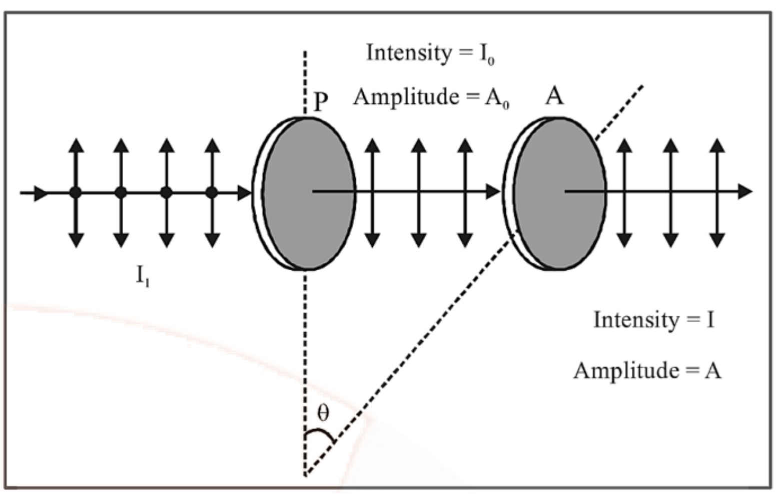


Note: If an unpolarized light is passed through a polarizer, the intensity of the transmitted polarized light will become half of the intensity of unpolarised light.

(iii) Polaroids are used in making wind shields of automobiles, sun glasses etc. They helps to reduce head light glare of cares and improve colour contrast in old paintings. Polaroids are also used in 3-D motion pictures are in optical stress analysis.

9.6 Malus law

The intensity of a polarised light passed through an analyser will change as the square of the cosine of the angle between the plane of transmission of the analyser and the plane of the polariser. This is known as Malus law.



$I = I_o \cos^2\theta$ and $A^2 = A_o^2 \cos^2\theta \Rightarrow A = A_o \cos\theta$

If $\theta = 0^o, I = I_o, A = A_o$

If $\theta = 45^o, I = \frac{I_o}{2}, A = \frac{A_o}{\sqrt{2}}$

If $\theta = 90^o, I = 0, A = 0$

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

So, $I_o = \frac{I_i}{2}$ i.e. if an unpolarised light is converted into plane polarized light (say by passing it through a Polaroid or a Nicole-prism), its intensity becomes half and $I = \frac{I_i}{2}\cos^2\theta$

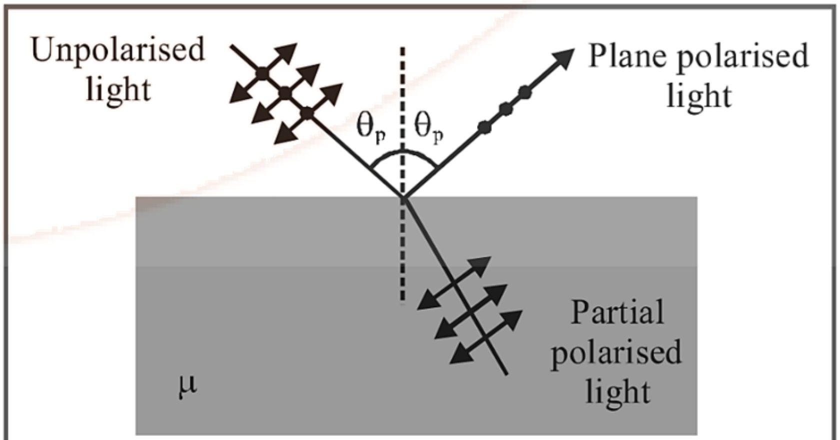
Note: Percentage of polarisation $= \frac{(I_{max} - I_{min})}{(I_{max} + I_{min})} \times 100$

9.7 Brewster's law

When a beam of unpolarised light is reflected from a transparent medium (having refractive index $= \mu$), the reflected light will be completely plane polarised at a certain angle of incidence (called the angle of polarisation θ_p). This is known as Brewster's law.

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

i. For $i < \theta_p$ or $i > \theta_p$



Polarisation by reflection

Both reflected and refracted rays becomes partially polarized

i. For glass $\theta_p \approx 57^o$, for water $\theta_p \approx 53^o$

10. VALIDITY OF RAY OPTICS

By diffraction of light travels, a parallel beam of light travels up to distances as large as few meters can be broadened.

10.1 Fresnel Distance

The minimum distance a beam of light can travel before its deviation from straight line path becomes significant/ noticeable is known as Fresnel distance.

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

As wavelength of light is very small, the deviation will be also very small and light can be assumed as travelling in a straight line.

So, we can neglect broadening of beam due to diffraction up to distances as large as a few meters, i.e., we can assume that light travels along straight lines and ray optics can be taken as a limiting case of wave optics.

Therefore, Ray optics can be considered as a limiting case of wave optics.

11. RESOLVING POWER

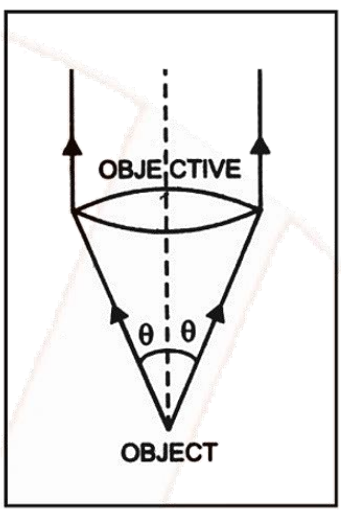
If two point objects are close to each other, images diffraction patterns of those objects will be also close and overlap each other.

Limit of resolution of the instrument is the minimum distance between two objects which can be seen separately by the object instrument.

$$\text{Resolving power (R.P)} = \frac{1}{\text{Limit of Revolution}}$$

11.1 Resolving power of Microscope

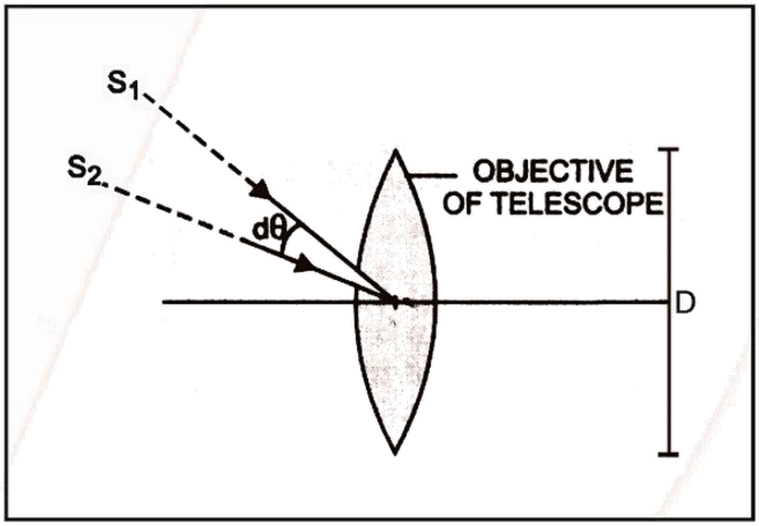
$$\text{R.P. of microscope} = \frac{2\mu \sin\theta}{\lambda}$$



11.2 Resolving power of Telescope

$$\text{R.P of telescope } = \frac{1}{d\theta} = \frac{D}{1.22\lambda}$$

Where D is aperture of telescope.


S1
S2
dθ
OBJECTIVE
OF TELESCOPE
D