Chapter 30
Wave Optics

Newton's Corpuscular Theory

(1) Newton thought that light is made up of tiny, light and elastic particles called corpuscles which are emitted by a luminous body.

(2) The corpuscles travel with speed equal to the speed of light in all directions in straight lines.

(3) The corpuscles carry energy with them. When they strike retina of the eye, they produce sensation of vision.

(4) The corpuscles of different colour are of different sizes (red corpuscles larger than blue corpuscles).

(5) The corpuscular theory explains that light carry energy and momentum, light travels in a straight line, Propagation of light in vacuum, Laws of reflection and refraction

(6) The corpuscular theory fails to explain interference, diffraction and polarization.

(7) A major prediction of the corpuscular theory is that the speed of light in a denser medium is more than the speed of light in a rarer medium. The truth is that the speed of the light is smaller in a denser medium. Therefore, the Newton's corpuscular theory is wrong.

Huygen's Wave Theory

(1) Wave theory of light was given by Christian Huygen. According to this, a luminous body is a source of disturbance in a hypothetical medium ether. This medium pervades all space.

(2) It is assumed to be transparent and having zero inertia. The disturbance from the source is propagated in the form of waves through the space.

(3) The waves carry energy and momentum. Huygen assumed that the waves were longitudinal. Further when polarization was discovered, then to explain it, light waves were, assumed to be transverse in nature by Fresnel.

(4) This theory explains successfully, the phenomenon of interference and diffraction apart from other properties of light.

(5) The Huygen's theory fails to explain photo-electric effect, Compton's effect *etc*.

(6) The wave theory introduces the concept of wavefront.

Wavefront

(1) Suggested by Huygens

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

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

(4) 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.

(5) 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

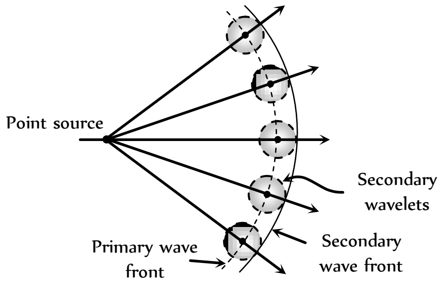
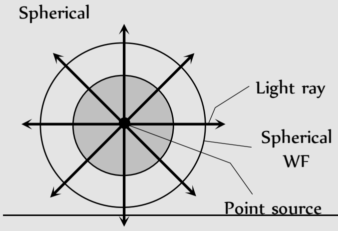
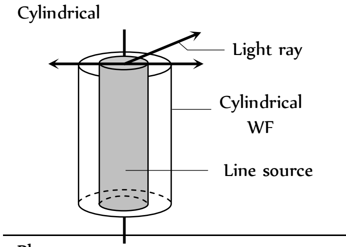
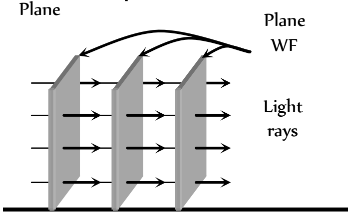


Fig. 30.1

Table 30.1 : Different types of wavefront

Type of wavefront	Intensity	Amplitude
Spherical 	$I \propto \frac{1}{r^2}$	$A \propto \frac{1}{r}$

Cylindrical 	$I \propto \frac{1}{r}$	$A \propto \frac{1}{\sqrt{r}}$
Plane 	$I \propto r^0$	$A \propto r^0$

Reflection and Refraction of Wavefront

Reflection

$BC = AD$

and $\angle i = \angle r$

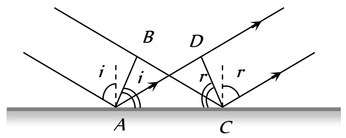


Fig. 30.2

Refraction

$$\frac{BC}{AD} = \frac{v_1}{v_2} = \frac{\sin i}{\sin r} = \frac{\mu_2}{\mu_1}$$

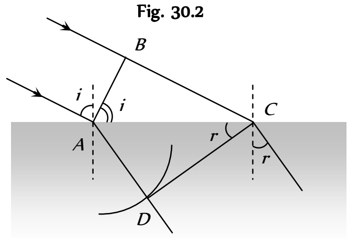


Fig. 30.3

Super Position of Waves

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.* $\vec{y} = \vec{y}_1 + \vec{y}_2$

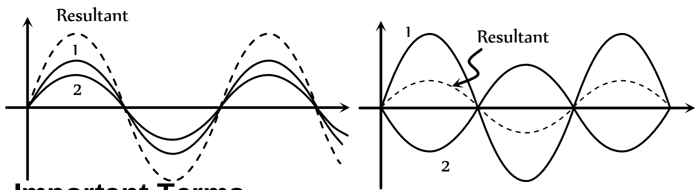


Fig. 30.4

Important Terms

(1) **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.

(2) **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

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

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

Resultant Amplitude and Intensity

Let us consider two waves that have the same frequency but have a certain fixed (constant) phase difference between them. Their super position shown below

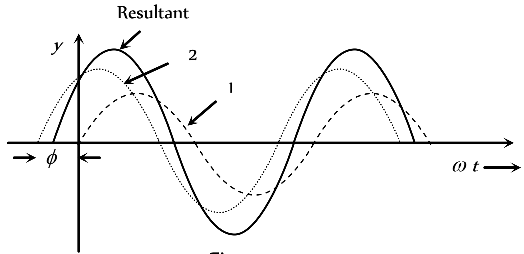


Fig. 30.5

Let the two waves are

$y_1 = a_1 \sin \omega t$ 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.

(1) **Resultant amplitude :** The resultant wave can be written as $y = A \sin(\omega t + \theta)$

where A = resultant amplitude $= \sqrt{a_1^2 + a_2^2 + 2a_1a_2 \cos\varphi}$

(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). Resultant intensity $I = I_1 + I_2 + 2\sqrt{I_1 I_2}\cos\phi$

For two identical source $I_1 = I_2 = I_0 \Rightarrow I = I_0 + I_0 + 2\sqrt{I_0 I_0}\cos\phi$

$= 4I_0 \cos^2\frac{\phi}{2}$ $\left[1 + \cos\theta = 2\cos^2\frac{\theta}{2}\right]$

Coherence

The phase relationship between two light waves can very from time to time and from point to point in space. The property of definite phase relationship is called coherence.

(1) **Temporal coherence :** In a light source a light wave (photon) is produced when an excited atom goes to the ground state and emits light.

(i) The duration of this transition is about 10^{-9} to 10^{-10} *sec.* Thus the emitted wave remains sinusoidal for this much time. This time is known as coherence time (τ_c).

(ii) Definite phase relationship is maintained for a length $L = c\tau_c$ called coherence length. For neon λ = 6328 Å, $\tau_c \approx 10^{-10}$ *sec* and L = 0.03 *m.*

For cadmium λ = 6438 Å, $\tau_c = 10^{-9}$ *sec* and L = 0.3 *m*

For Laser $\tau_c = 10^{-5}$ *sec* and L = 3 *km*

(iii) The spectral lines width $\Delta\lambda$ is related to coherence length L and coherence time τ_c. $\Delta\lambda \approx \frac{\lambda^2}{c\tau_c}$ or $\Delta\lambda \approx \frac{\lambda^2}{L}$

(2) **Spatial coherence :** Two points in space are said to be spatially coherence if the waves reaching there maintains a constant phase difference

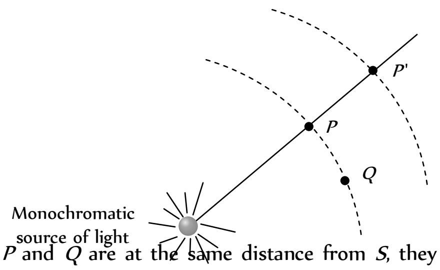


Fig. 30.6

Points P and Q are at the same distance from S, they will always be having the same phase. Points P and P' will be spatially coherent if the distance between P and P' is much less than the coherence length *i.e.* $PP' << c\tau_c$

(3) **Methods of obtaining coherent sources :** Two coherent sources are produced from a single source of light by two methods (i) By division of wavefront and (ii) By division of amplitude

(i) **Division of wave front :** The wave front emitted by a narrow source is divided in two parts by reflection, refraction or diffraction.

The coherent sources so obtained are imaginary. There produced in Fresnel's biprism, Llyod's mirror Youngs' double slit *etc.*

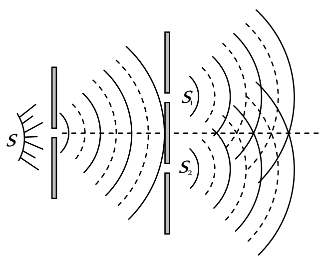


Fig. 30.7

(ii) **Division of amplitude :** In this arrangement light wave is partly reflected (50%) and partly transmitted (50%) to produced two light rays.

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 real and are obtained in Newton's rings, Michelson's interferrometer, colours in thin films.

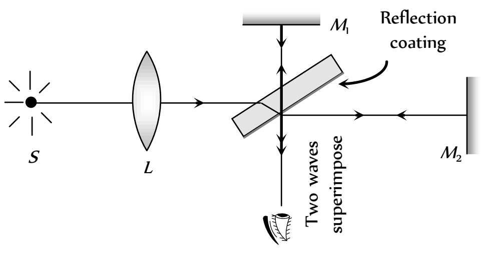
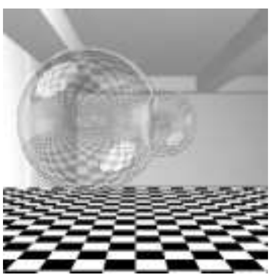


Fig. 30.8

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. It is of following two types

(1) **Constructive interference :** When the waves meets a point with same phase, constructive interference is obtained at that point (*i.e.* maximum light)

(i) Phase difference between the waves at the point of observation $\phi = 0^o$ or $2n\pi$

(ii) Path difference between the waves at the point of observation $\Delta = n\lambda$ (*i.e.* even multiple of $\lambda/2$)

(iii) Resultant amplitude at the point of observation will be maximum $A_{max} = a_1 + a_2$

If $a_1 = a_2 = a_0 \Rightarrow A_{\max} = 2a_0$

(iv) Resultant intensity at the point of observation will be maximum

$$I_{\max} = I_1 + I_2 + 2\sqrt{I_1 I_2} = \left(\sqrt{I_1} + \sqrt{I_2}\right)^2$$

If $I_1 = I_2 = I_0 \Rightarrow I_{\max} = 4I_0$

(2) **Destructive interference :** When the wave meets a point with opposite phase, destructive interference is obtained at that point (*i.e.* minimum light)

(i) Phase difference $\phi = 180^o$ or $(2n-1)\pi$; $n = 1, 2, ...$

or $(2n+1)\pi$; $n = 0, 1, 2.....$

(ii) Path difference $\Delta = (2n-1)\frac{\lambda}{2}$ (*i.e.* odd multiple of $\lambda/2$)

(iii) Resultant amplitude at the point of observation will be minimum $A_{\min} = a_1 - a_2$

If $a_1 = a_2 \Rightarrow A_{\min} = 0$

(iv) Resultant intensity at the point of observation will be minimum

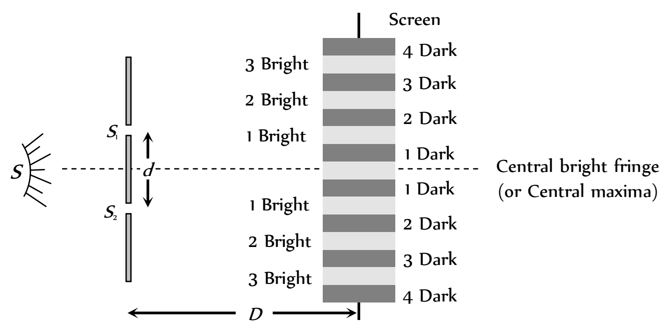
$$I_{\min} = I_1 + I_2 - 2\sqrt{I_1 I_2} = \left(\sqrt{I_1} - \sqrt{I_2}\right)^2$$

If $I_1 = I_2 = I_0 \Rightarrow I_{\min} = 0$

(3) **Super position of waves of random phase difference :** When two waves (or more waves) having random phase difference between them super impose, then no interference pattern is produced. Then the resultant intensity is just the sum of the two intensities. $I = I_1 + I_2$

Young's Double Slit Experiment (YDSE)

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



d = Distance between slits
D = Distance between slits and screen
λ = Wavelength of monochromatic light emitted from source

(1) Central fringe is always bright, because at central position $\phi = 0^o$ or $\Delta = 0$

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

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

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

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

Useful Results

(1) **Path difference :** Path difference between the interfering waves meeting at a point P on the screen is given by

$\Delta = \Delta_i + \Delta_f$; where Δ_i = initial path difference between the waves before the slits and Δ_f = path difference between the waves after emerging from the slits. In this case $\Delta_i = 0$ (Commonly used condition). So

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

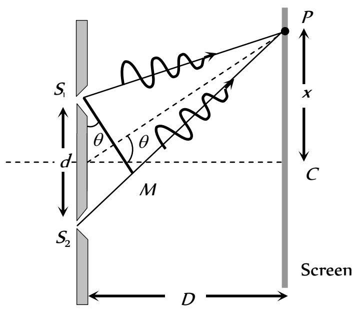


Fig. 30.10

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, ...

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

Position of n^{th} dark fringe from central maxima

$$x_n = \frac{(2n-1)\lambda D}{2d} = \frac{(2n-1)\beta}{2} \; ; \; n = 1, 2, 3 ....$$

(3) **Fringe width (β) :** The separation between any two consecutive bright or dark fringes is called fringe width. In *YDSE* all fringes are of equal width. Fringe width $\beta = \frac{\lambda D}{d}$.

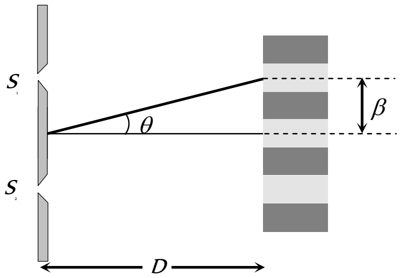


Fig. 30.11

and angular fringe width $\theta = \frac{\lambda}{d} = \frac{\beta}{D}$

(4) 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 $\boldsymbol{n_1\lambda_1 = n_2\lambda_2}$.

(5) **Separation (Δx) between fringes**

(i) Between n^{th} bright and m^{th} bright fringes $(n > m)$

$$\Delta x = (n - m)\beta$$

(ii) Between n^{th} bright and m^{th} dark fringe

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

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

(6) **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.

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

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

Condition for Observing Interference

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

(2) 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.

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

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

(5) 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.

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 towards the slit in front of which glass plate is placed.

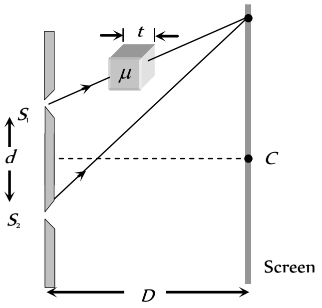


Fig. 30.12

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

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

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

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

(5) Shift is independent of wavelength.

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 $I_{max} = I_{min}, V = 0$

Missing Wavelength in Front of One Slit in YDSE

Suppose P is a point of observation infront of slit S_1 as shown

Missing wavelength at P

$$\lambda = \frac{d^2}{(2n-1)D}$$

By putting $n = 1, 2, 3....$

Missing wavelengths are

$$\lambda = \frac{d^2}{D}, \frac{d^2}{3D}, \frac{d^2}{5D}....$$

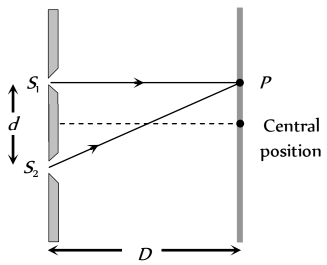
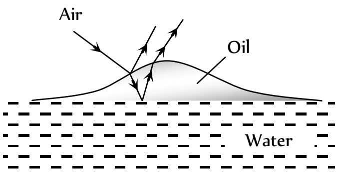


Fig. 30.13

Interference in Thin Films

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.



Oil film on water surface

Fig. 30.14

In thin films interference takes place between the waves reflected from it's two surfaces and waves refracted through it.

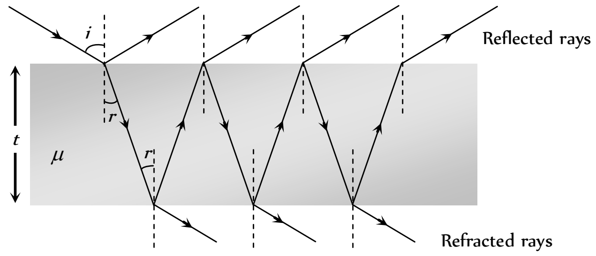


Fig. 30.15

(1) **Interference in reflected light :** Condition of constructive interference (maximum intensity)

$$\Delta = 2\mu\ t\cos r = (2n-1)\frac{\lambda}{2}.$$

For normal incidence $r = 0$ so $2\mu t = (2n-1)\frac{\lambda}{2}$

Condition of destructive interference (minimum intensity)

$\Delta = 2\mu t \cos r = (2n)\frac{\lambda}{2}$. For normal incidence $2\mu t = n\lambda$

(2) **Interference in refracted light :** 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)

$$\Delta = 2\mu t \cos r = (2n-1)\frac{\lambda}{2}$$

For normal incidence $2\mu t = (2n-1)\frac{\lambda}{2}$

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.

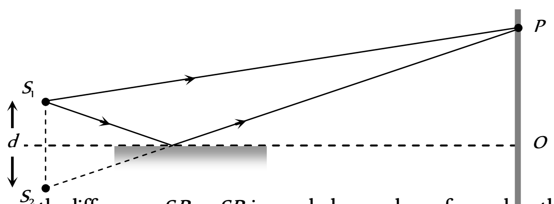


Fig. 30.16

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. 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)

Fresnel's Biprims

(1) It is an optical device of producing interference of light Fresnel's biprism is made by joining base to base two thin prism of very small angle

(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 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 $\beta = \dfrac{\lambda D}{d}$

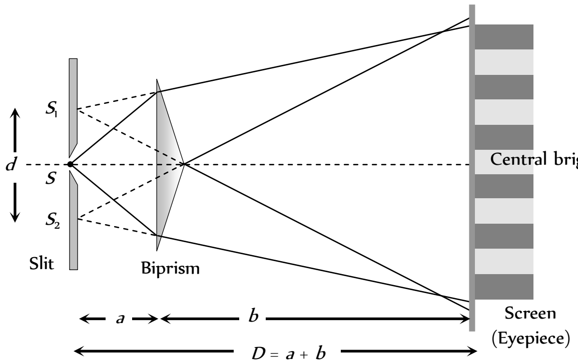


Fig. 30.17

(6) 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 $d = 2a(\mu - 1)\alpha$

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

(7) If a convex lens is mounted between the biprism and eye piece. There will be two positions of lens when the sharp images of coherent sources will be observed in the eyepiece. The separation of the images in the two positions are measured. Let these be d_1 and d_2 then $d = \sqrt{d_1 d_2}$

$$\therefore \; \lambda = \frac{\beta d}{D} = \frac{\beta\sqrt{d_1 d_2}}{(a+b)}.$$

Newton's Rings

(1) If we place a plano-convex lens on a plane glass surface, a thin film of air is formed between the curved surface of the lens and plane glass plate.

(2) If we allow monochomatic light to fall normally on the surface of lens, then circular interference fringes of radius r can be seen in the reflected light. This circular fringes are called Newton rings.

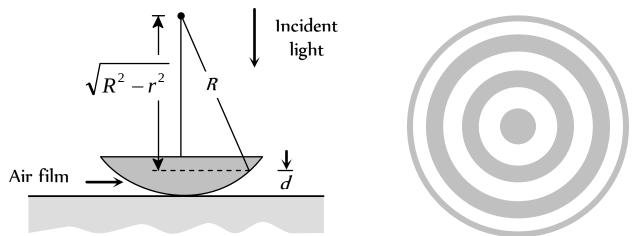


Fig. 30.18

(3) The central fringe is a dark spot then there are alternate bright and dark fringes (Ring shape).

(4) Radius of n^{th} dark ring $r_m \simeq \sqrt{\lambda R}$

$n = 0, 1, 2, \ldots\ldots$, R = Radius of convex surface

(5) Radius of n^{th} bright ring $r_n = \sqrt{\left(n + \dfrac{1}{2}\right)\lambda R}$

(6) If a liquid of ref index μ is introduced between the lens and glass plate, the radii of dark ring would be $r_n = \sqrt{\dfrac{n\lambda R}{\mu}}$

(7) Newton's ring arrangement is used of determining the wavelength of monochromatic light. For this the diameter of n^{th} dark ring (D_n) and $(n + p)^{th}$ dark ring (D_{n+p}) are measured then

$$D_{(n+p)}^2 = 4(n+p)\lambda R \text{ and } D_n^2 = 4n\lambda R \quad \Rightarrow \quad \lambda = \frac{D_{n+p}^2 - D_n^2}{4pR}$$

Doppler's Effect of 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

(1) **Source of light moves towards the stationary observer :** When a light source is moving towards an observer with a relative velocity v then the apparent frequency (ν') is greater than the actual frequency (ν) of light. Thus apparent wavelength (λ') is lesser the actual wavelength (λ).

$$\nu' = \nu\sqrt{\frac{(1 + v/c)}{(1 - v/c)}} \text{ and } \lambda' = \lambda\sqrt{\frac{(1 - v/c)}{(1 + v/c)}}$$

For $v << c$:

(i) Apparent frequency $\nu' = \nu\left(1 + \dfrac{v}{c}\right)$ and

(ii) Apparent wavelength $\lambda' = \lambda\left(1 - \dfrac{v}{c}\right)$

(iii) Doppler's shift : Apparent wavelength < actual wavelength,

So spectrum of the radiation from the source of light shifts towards the violet end of spectrum. This is called violet shift

Doppler's shift $\Delta\lambda = \lambda . \dfrac{v}{c}$

(iv) The fraction decrease in wavelength $= \dfrac{\Delta\lambda}{\lambda} = \dfrac{v}{c}$

(2) **Source of light moves away from the stationary observer :** In this case $\nu' < \nu$ and $\lambda' > \lambda$

$$\nu' = \nu\sqrt{\frac{(1 - v/c)}{(1 + v/c)}} \text{ and } \lambda' = \lambda\sqrt{\frac{(1 + v/c)}{(1 - v/c)}}$$

For $v << c$:

(i) Apparent frequency $\nu' = \nu\left(1 - \dfrac{v}{c}\right)$ and

(ii) Apparent wavelength $\lambda' = \lambda\left(1+\frac{v}{c}\right)$

(iii) Doppler's shift : Apparent wavelength > actual wavelength,

So spectrum of the radiation from the source of light shifts towards the red end of spectrum. This is called red shift

Doppler's shift $\Delta\lambda = \lambda.\frac{v}{c}$

(iv) The fractional increase in wavelength $= \frac{\Delta\lambda}{\lambda} = \frac{v}{c}$.

(3) **Doppler broadening :** For a gas in a discharge tube, atoms are moving randomly in all directions. When spectrum of light emitted from these atoms is analyzed, then due to Doppler effect (because some atoms are moving towards detector, some atoms are moving away from detector), the frequency of a spectral line is not observed as having one value, but is spread over a range

$$\pm\Delta\nu = \pm\frac{v}{c}\nu, \quad \pm\Delta\lambda = \pm\frac{v}{c}\lambda$$

This broadens the spectral line by an amount $(2\Delta\lambda)$. It is called Doppler broadening. The Doppler broadening is proportional to v, which in turn is proportional to $\sqrt{T}$, where T is the temperature in Kelvin.

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

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

$\Delta\nu = \frac{2v}{c}\nu$. (The factor of 2 arises due to refection of waves). For a receding target $\Delta\nu = -\frac{2v}{c}\nu$. (The minus sign indicates decrease in frequency).

(5) **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.

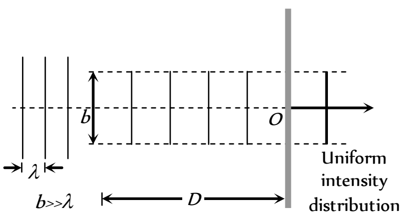
(v) Tracking of satellites.

(vi) In medical sciences in echo cardiogram, sonography *etc*.

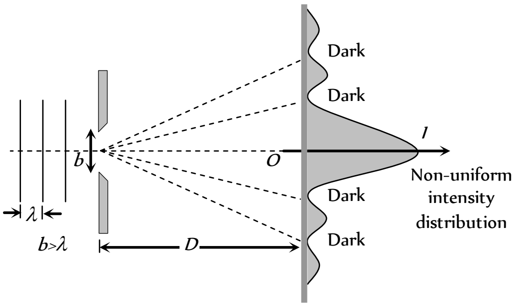
Diffraction of Light

The phenomenon of diffraction was first discovered by Girmaldi. It's experimental study was done by Newton's and young. The theoretical explanation was first given by Fresnel's.

(1) The phenomenon of bending of light around the corners of an obstacle/aperture of the size of the wave length of light is called diffraction.



(A) Size of the slit is very large compared to wavelength



(B) Size of the slit is comparable to wavelength

(2) The phenomenon resulting from the superposition of secondary wavelets originating from different parts of the same wave front is define as diffraction of light.

(3) Diffraction is the characteristic of all types of waves.

(4) Greater the wave length of wave higher will be it's degree of diffraction.

Types of Diffraction

(1) **Fresnel diffraction :** If either source or screen or both are at finite distance from the diffracting device (obstacle or aperture), the diffraction is called Fresnel type.

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

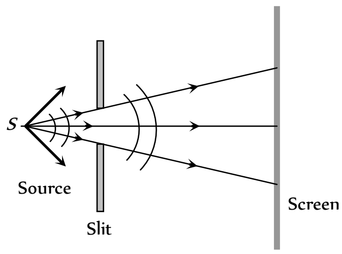


Fig. 30.20

(2) **Fraunhofer diffraction :** 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.

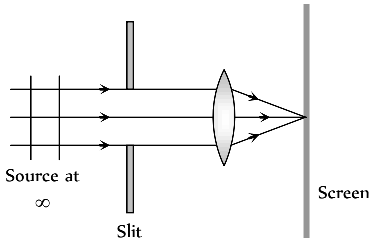
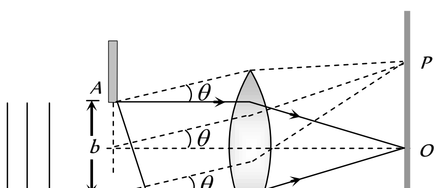


Fig. 30.21

Diffraction at Single Slit (Fraunhoffer Diffraction)

Suppose a plane wave front is incident on a slit AB (of width b). Each and every part of the expose part of the plane wave front (i.e. every part of the slit) acts as a source of secondary wavelets spreading in all directions. The diffraction is obtained on a screen placed at a large distance. (In practice, this condition is achieved by placing the screen at the focal plane of a converging lens placed just after the slit).



(1) The diffraction pattern consists of a central bright fringe (central maxima) surrounded by dark and bright lines (called secondary minima and maxima).

(2) At point O on the screen, the central maxima is obtained. The wavelets originating from points A and B meets in the same phase at this point, hence at O, intensity is maximum.

(3) **Secondary minima :** For obtaining n secondary minima at P on the screen, path difference between the diffracted waves $\Delta = b\sin\theta = n\lambda$

(i) Angular position of n secondary minima $\sin\theta \approx \theta = \dfrac{n\lambda}{b}$

(ii) Distance of n secondary minima from central maxima

$x_n = D.\theta = \dfrac{n\lambda D}{b} = \dfrac{n\lambda f}{b}$; where D = Distance between slit and screen. $f \approx D$ = Focal length of converging lens.

(4) **Secondary maxima :** For n secondary maxima at P on the screen.

Path difference $\Delta = b\sin\theta = (2n+1)\dfrac{\lambda}{2}$; where n = 1, 2, 3 .....

(i) Angular position of n secondary maxima

$$\sin \approx \theta \approx \frac{(2n+1)\lambda}{2b}$$

(ii) Distance of n secondary maxima from central maxima

$$x_n = D.\theta = \frac{(2n+1)\lambda D}{2b} = \frac{(2n+1)\lambda f}{2b}$$

(5) **Central maxima :** The central maxima lies between the first minima on both sides.

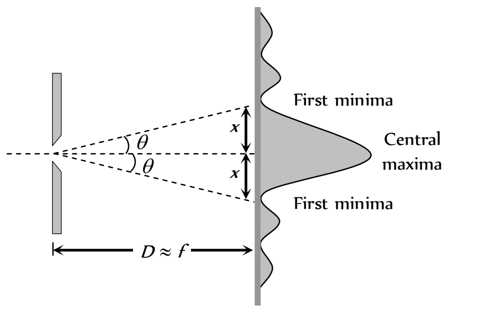
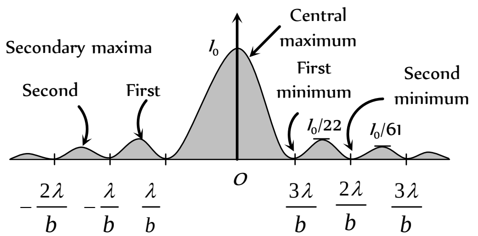


Fig. 30.23

(i) The Angular width d central maxima = $2\theta = \dfrac{2\lambda}{b}$

(ii) Linear width of central maxima $= 2x = 2D\theta = 2f\theta = \dfrac{2\lambda f}{b}$

(6) **Intensity distribution :** If the intensity of the central maxima is I_0 then the intensity of the first and second secondary maxima are found to be $\dfrac{I_0}{22}$ and $\dfrac{I_0}{61}$. Thus diffraction fringes are of unequal width and unequal intensities.



(i) The mathematical expression for in intensity distribution on the screen is given by

$I = I_o\left(\dfrac{\sin\alpha}{\alpha}\right)^2$ where α is just a convenient connection between the angle θ that locates a point on the viewing screening and light intensity I.

ϕ = Phase difference between the top and bottom ray from the slit width b.

Also $\alpha = \dfrac{1}{2}\phi = \dfrac{\pi b}{\lambda}\sin\theta$

(ii) As the slit width increases (relative to wavelength) the width of the control diffraction maxima decreases; that is, the light undergoes less flaring by the slit. The secondary maxima also decreases in width (and becomes weaker).

(iii) If $b >> \lambda$, the secondary maxima due to the slit disappear; we then no longer have single slit diffraction.

(iv) When the slit width is reduced by a factor of 2, the amplitude of the wave at the centre of the screen is reduced by a factor of 2, so the intensity at the centre is reduced by a factor of 4.

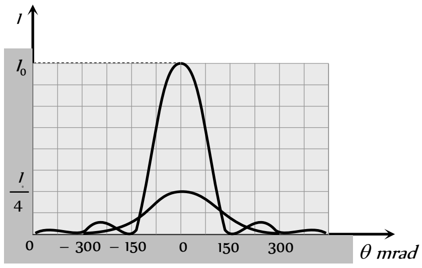


Fig. 30.25

Diffraction Gratings

One of the most useful tools in the study of light and of objects that emit and absorbs light is the diffraction grating.

(1) this device consists parallel slits of equal width and equal spacing called rulings, perhaps as many as several thousand per mm.

(2) The separation (d) between rulings is called grating spacing. (If N-rulings occupy a total width ω, then $d = \dfrac{\omega}{N}$)

(3) For light ray emerging from each slit at an angle θ, there is a path difference $d\sin\theta$, between each ray the one directly above. The d is called the grating element

$d = a + e$

where a = width of the slit

e = opaque part

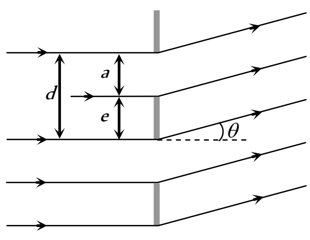


Fig. 30.26

(4) The condition for formation of bright fringe is $d \sin\theta = n\lambda$, where $n = 0, 1, 2, ...$ is called the order of diffraction.

Fresnel's Half Period Zone (HPZ)

According to Fresnel's the entire wave front can be divided into a large number of parts of zones which are known as Fresnel's half period zones (HPZ's).

The resultant effect at any point on screen is due to the combined effect of all the secondary waves from the various zones.

Suppose ABCD is a plane wave front. We desire to find it's effect at point P consider a sphere of radius $\left(d+\dfrac{\lambda}{2}\right)$ with centre at P, then this sphere will cut the wave front in a circle (circle 1). This circular zone is called Fresnel's first (I) HPZ.

A sphere of radius $b+2\left(\dfrac{\lambda}{2}\right)$ with centre at P will cut the wave front in circle 2, the annular region between circle 2 and circle 1 is called second (II) HPZ.

The peripheral area enclosed between the n circle and $(n-1)^{th}$ circle is defined as n HPZ.

(1) **Radius of HPZ :** For n HPZ, it is given by

$$r_n = \sqrt{nd\lambda} \;\; \Rightarrow r_n \propto \sqrt{\lambda}$$

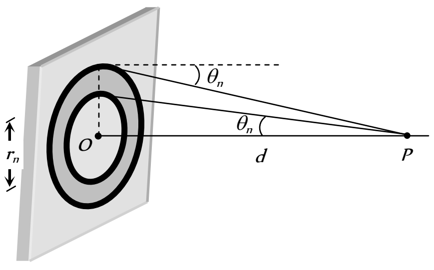


Fig. 30.28

(2) **Area of HPZ :** Area of n HPZ is given by

A_n = Area of n circle – Area of $(n-1)^{th}$ circle

$= \pi(r_n^2 - r_{n-1}^2) = \pi d\lambda$

(3) **Mean distance of the observation point P from n HPZ :** $d_n = \dfrac{r_n + r_{n-1}}{2} = b + \dfrac{(2n-1)\lambda}{4}$

(4) **Phase difference between the HPZ :** phase difference between the wavelets originating from two consecutive HPZ's and reaching the point P is π (or path difference is $\dfrac{\lambda}{2}$, time difference is $\dfrac{T}{2}$).

The phase difference between any two even or old number HPZ is 2π.

(5) **Amplitude of HPZ :** The amplitude of light at point P due to n HPZ is $R_n \propto \dfrac{A_n}{d_n}(1+\cos\theta_n)$; where A_n = Area of n HPZ, d_n = Mean distance of n HPZ

$(1+\cos\theta_n)$ = Obliquity factor.

On increasing the value of n, the value of R_n gradually goes on decreasing i.e. $R_1 > R_2 > R_3 > R_4 > .... > R_{n-1} > R_n$

(6) **Resultant Amplitude :** The wavelets from two consecutive HPZ's meets in opposite phase at P.

Hence Resultant amplitude at P

$$R = R_1 - R_2 + R_3 - R_4 + ...(-1)^{n-1} R_n$$

When $n = \infty$, then $R_{n-1} = R_n = 0$, therefore $R = \dfrac{R_1}{2}$

i.e. For large number of HPZ, the amplitude of light at point P due to whole wave front is half the amplitude due to first HPZ.

The ratio of amplitudes due to consecutive HPZ's is constant and is less than 1

$$\frac{R_n}{R_{n-1}} .... \frac{R_5}{R_4} = \frac{R_4}{R_3} = \frac{R_3}{R_2} = \frac{R_2}{R_1} = k \qquad \text{(where } k < 1)$$

(7) **Resultant Intensity :** Intensity $\propto$ (amplitude)^2

For $n = \infty$, $I \propto \dfrac{R_1^2}{4} \propto \dfrac{I_1}{4}$

i.e. the resultant intensity due to whole wave front is $\dfrac{1}{4}th$ the intensity due to first HPZ.

Diffraction Due to a Circular Disc

When a disc is placed in the path of a light beam, then diffraction pattern is formed on the screen.

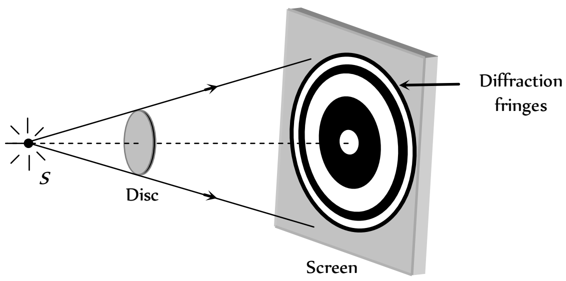


Fig. 30.29

(1) At the centre of the circular shadow of disc, there occurs a bright spot. This spot is called Fresnel's spot or Poisson's spot.

(2) The intensity of bright spot decreases, when the size of the disc is increased or when the screen is moved towards the disc.

(3) Circular alternate bright and dark fringes are formed around the bright spot with fringe width in decreasing order.

(4) Let r be the radius of the disc, d is the distance between screen and the disc and λ is the wavelength of light used.

If n HPZ are covered by disc then $nd\lambda = \pi r^2 \Rightarrow n = \frac{r^2}{d\lambda}$

(5) If the disc obstruct only first HPZ, the resultant amplitude at the central point $R = -R_2 + R_3 + ... \approx -\frac{R_2}{2}$.

So intensity is $\frac{kR_2^2}{4}$ which is slightly less than the intensity $\frac{k\,R_1^2}{4}$ due to whole wave front, when no obstacle is placed.

(6) The intensity at bright spot is given by $I = k\left[\frac{R_{n+1}}{2}\right]^2$

where n = Number of obstructed HPZ's

Diffraction Due to a Circular Aperture

When a circular aperture is placed in the path of a light beam, then following diffraction pattern is formed on the screen.

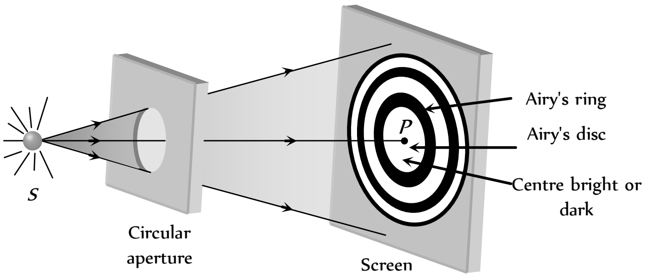
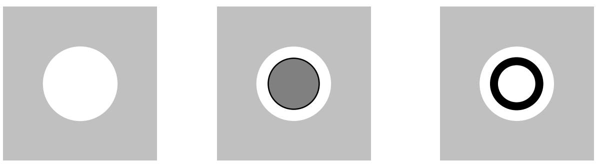


Fig. 30.30

(1) If only one HPZ is allowed by the aperture then the resultant amplitude at P would be R_1 which is twice the value of amplitude for the unobstructed wave front. The intensity would there fore be $4I$, where I represents the intensity at point P, due to unobstructed wave front.

(2) If the first two HPZ's are permitted by aperture than the resultant intensity at the centre point P will be very small (as $R_1 - R_2 \approx 0$). In this case the diffraction pattern consist of a bright circle of light with a dark spot.

(3) In general if number of HPZ's (n) passing through aperture is odd, then the central point will be bright and if n is even, central point will be dark.



(A) n=1, r^2=$b\lambda$ bright centre | (B) n=2, r^2=2$b\lambda$ dark centre | (C) n=3, r^2=3$b\lambda$ bright centre

Fig. 30.31

(4) The central bright disc is known as Airy's disc.

(5) In the non axial region bright and dark diffraction rings are obtained. The intensity of bright diffraction rings gradually goes on decreasing whereas that of dark diffraction goes on increasing.

(6) The first dark ring obtained around the central bright disc is known as Airy's ring.

Zone Plate

It is a diffracting device used to experimentally demonstrate the diffraction effect.

(1) It is formed on a glass plate by drawing a number of concentric circles on it whose radii are in the ratio of

$$\sqrt{1} : \sqrt{2} : \sqrt{3}.......... \; .i.e.\, r \propto \sqrt{n}$$

For some specific distance from this plate the circles coincides with the HPZ's of the Fresnel's theory. (Alternate zones are made opaque).

(2) **Positive zone plate :** When odd zones are kept transparent to the light and even zones are made opaque, then it is called positive zone plate.

The resultant amplitude due to this zone plate in

$$R = R_1 + R_3 + R_5 + ... >> \frac{R_1}{2}$$

Thus, intensity of light tremendously increases.

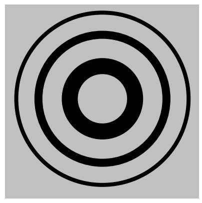


Fig. 30.32

(3) **Negative zone plate :** when even zones are kept transparent to light and odd zones are made opaque, then it is called negative zone plate.

The resultant amplitude due to this zone plate is

$$R = R_2 + R_4 + R_6 + ... >> \frac{R_1}{2}$$

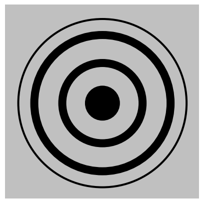


Fig. 30.33

(4) Zone plate behaves like a convex lens. For a plane wave front the image of source is formed at distance d *i.e.* d is equal to the principle focal length or first focal length $f_1 = d = \frac{r^2}{\lambda}$

(5) Multiple focii of zone plate are given by $f_p = \frac{r^2}{(2p-1)\lambda}$ where p = 1, 2, 3,......... represents the order of focii

(6) If the radius of n circle on zone plate is r_n then in terms of r_n.

Principal focal length $f_1 = \frac{r_n^2}{n\lambda}$

Other focal length $f_p = \frac{r_n^2}{(2p-1)n\lambda}$

(7) If a is the distance of the source from the zone plate then the distance b of the point where maximum intensity is observes is given by $\frac{1}{a} + \frac{1}{b} = \frac{n\lambda}{r_n^2}$

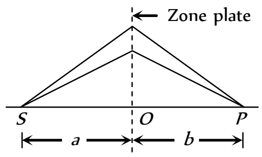


Fig. 30.34

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 :** In ordinary light (light from sun, bulb *etc.*) the electric field vectors are distributed in all directions in a light is called unpolarised light. The oscillation of propagation of light wave. This resolved into horizontal and vertical component.

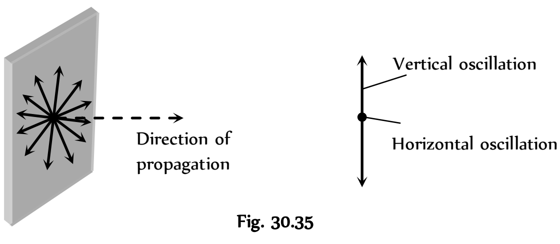


Fig. 30.35

(2) **Polarised light :** The phenomenon of limiting the vibrating of electric field vector in one direction in a plane perpendicular to the direction of propagation of light wave is called polarization of 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.

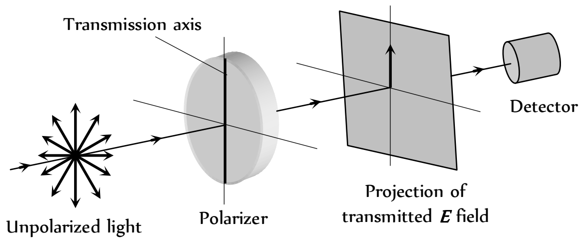
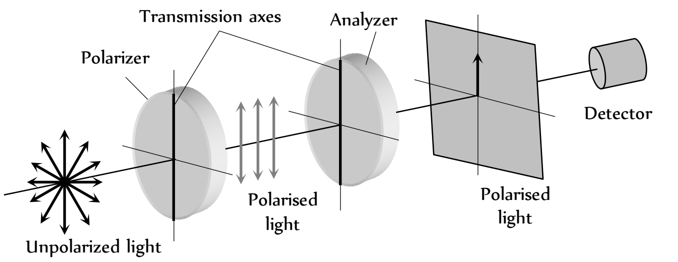


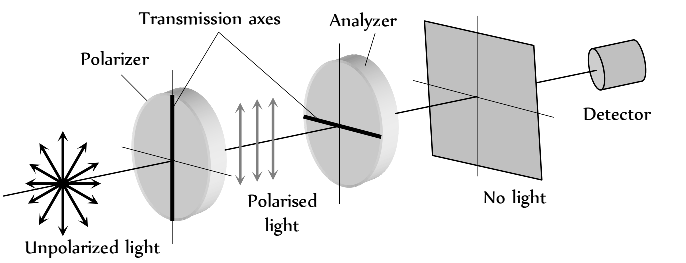
Fig. 30.36

(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.



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



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

Fig. 30.37

(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.

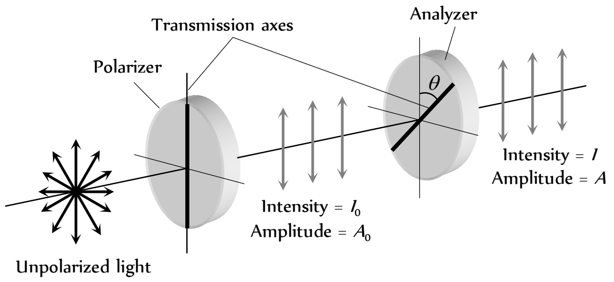


Fig. 30.38

(i) $I = I_0 \cos^2\theta$ and $A^2 = A_0^2 \cos^2\theta \Rightarrow A = A_0 \cos\theta$

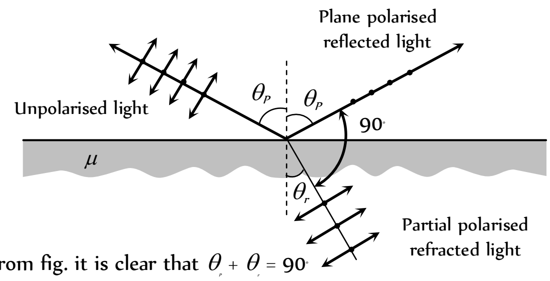
If $\theta = 0^o$, $I = I_0$, $A = A_0$, If $\theta = 90^o$, $I = 0$, $A = 0$

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

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

Methods of Producing Polarised Light

(1) **Polarisation by reflection :** Brewster discovered that when a beam of unpolarised light is reflected from a transparent medium (refractive index $=\mu$), the reflected light is completely plane polarised at a certain angle of incidence (called the angle of polarisation θ_p).



From fig. it is clear that $\theta_p + \theta_r = 90^\circ$

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

Fig. 30.39

(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 $\theta_P \approx 53^o$

(2) **By Dichroism :** Some crystals such as tourmaline and sheets of iodosulphate of quinine have the property of strongly absorbing the light with vibrations perpendicular to a specific direction (called transmission axis) transmitting the light with vibrations parallel to it. This selective absorption of light is called dichroism.

(3) **By double refraction :** In certain crystals, like calcite, quartz and tourmaline *etc*, incident unpolarized light splits up into two light beams of equal intensities with perpendicular polarization.

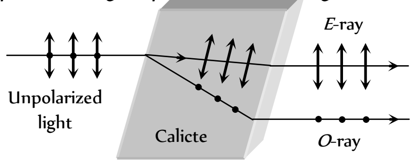


Fig. 30.40

(i) One of the ray is ordinary ray (*O*-ray) it obey's the Snell's law. Another ray's extra ordinary ray (*E*-ray) it doesn't obey's the Snell's law.

(ii) Along a particular direction (fixed in the crystal, the two velocities (velocity of *O*-ray v_o and velocity of *E*-ray v_e) are equal; this direction is known as the optic axis of the crystal (crystal's known as uniaxial crystal). Optic axis is a direction and not any line in crystal.

(iii) In the direction, perpendicular to the optic axis for negative crystal (calcite) $v_e > v_o$ and $\mu_e < \mu_o$.

For positive crystal $v_e < v_o$, $\mu_e > \mu_o$.

(4) **Nicol prism :** Nicol prism is made up of calcite crystal and in it *E*-ray is isolated from *O*-ray through total internal reflection of *O*-ray at canada balsam layer and then absorbing it at the blackened surface as shown in fig.

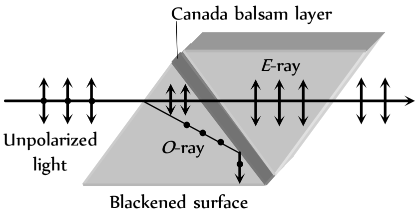


Fig. 30.41

The refractive index for the *O*-ray is more that for the *E*-ray. The refractive index of Canada balsam lies between the refractive indices of calcite for the *O*-ray and *E*-ray

(5) **By Scattering :** It is found that scattered light in directions perpendicular to the direction of incident light is completely plane polarised while transmitted light is unpolarised. Light in all other directions is partially polarised.

(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.

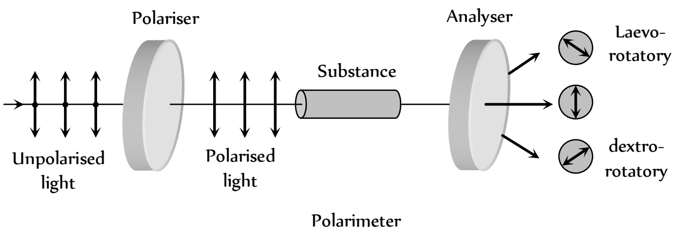


Fig. 30.42

If the optically active substance rotates the plane of polarisation clockwise (looking against the direction of light), it is said to be *dextro-rotatory* or *right-handed.* However, if the substance rotates the plane of polarisation anti-clockwise, it is called *laevo-rotatory* or *left-handed.*

The optical activity of a substance is related to the asymmetry of the molecule or crystal as a whole, *e.g.,* a solution of cane-sugar is dextro-rotatory due to asymmetrical molecular structure while crystals of quartz are dextro or laevo-rotatory due to structural asymmetry which vanishes when quartz is fused.

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

where θ is the rotation in length L at concentration C.

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

(i) By determining the polarising angle and using Brewster's law, *i.e.* $\mu = \tan\theta$, 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'.

(ix) A polarised light is used to study surface of nucleic acids (DNA, RNA)

Electromagnetic Waves

A changing electric field produces a changing magnetic field and vice versa which gives rise to a transverse wave known as electromagnetic wave. The time varying electric and magnetic field are mutually perpendicular to each other and also perpendicular to the direction of propagation of this wave.

The electric vector is responsible for the optical effects of an EM wave and is called the *light vector*.

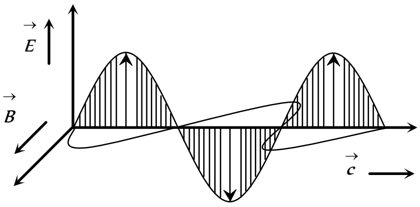


Fig. 30.43

(1) $\vec{E}$ and $\vec{B}$ always oscillates in phase.

(2) $\vec{E}$ and $\vec{B}$ are such that $\vec{E} \times \vec{B}$ is always in the direction of propagation of wave.

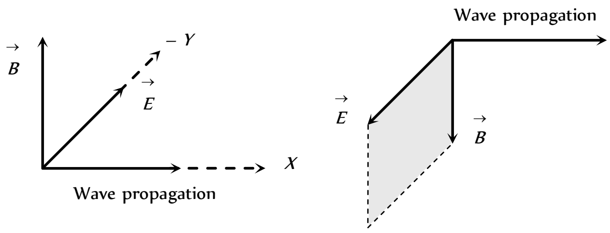


Fig. 30.44

(3) The EM wave propagating in the positive *x*-direction may be represented by

$$E = E_y = E_0 \sin(kx - \omega t)$$

$$B = B_z = B_0 \sin(kx - \omega t)$$

where E (or E_y), B (or B_z) are the instantaneous values of the fields, E_0, B_0 are amplitude of the fields and K = angular wave number $= \dfrac{2\pi}{\lambda}$.

Maxwell's Contribution

(1) **Ampere's Circuital law :** According to this law the line integral of magnetic field along any closed path or circuit is μ_0 times the total current threading the closed circuit *i.e.*, $\oint \vec{B}.\vec{dl} = \mu_0 i$

(2) **Inconsistency of Ampere's law :** Maxwell explained that Ampere's law is valid only for steady current or when the electric field does not change with time. To see this inconsistency consider a parallel plate capacitor being charged by a battery. During the charging time varying current flows through connecting wires.

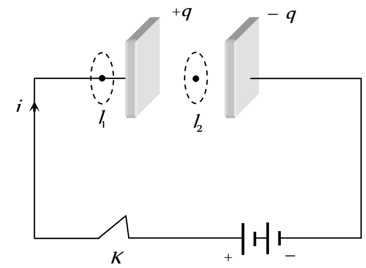


Fig. 30.45

Applying Ampere's law for loop l_1 and l_2 $\oint_{l_1} \vec{B}.\vec{dl} = \mu_0 i$

But $\oint_{l_2} \vec{B}.\vec{dl} = 0$ (Since no current flows through the region between the plates). But practically it is observed that there is a magnetic field between the plates. Hence Ampere's law fails

i.e. $\oint_{l_1} \vec{B}.\vec{dl} \neq \mu_0 i$.

(3) **Modified Ampere's Circuital law or Ampere- Maxwell's Circuital law :** Maxwell assumed that some sort of current must be flowing between the capacitor plates during charging process. He named it displacement current. Hence modified law is as follows

$$\oint \vec{B}.\vec{dl} = \mu_0 (i_c + i_d) \quad \text{or} \quad \oint \vec{B}.\vec{dl} = \mu_0 (i_c + \varepsilon_0 \frac{d\phi_E}{dt})$$

where i_c = conduction current = current due to flow of charges in a conductor and

i_d = Displacement current = $\varepsilon_0 \frac{d\phi_E}{dt}$ = current due to the changing electric field between the plates of the capacitor

(4) **Maxwell's equations**

(i) $\oint_s \vec{E}.\vec{ds} = \frac{q}{\varepsilon_0}$ (Gauss's law in electrostatics)

(ii) $\oint_s \vec{B}.\vec{ds} = 0$ (Gauss's law in magnetism)

(iii) $\oint \vec{B}.\vec{dl} = -\frac{d\phi_B}{dt}$ (Faraday's law of EMI)

(iv) $\oint \vec{B}\ \vec{dl} = \mu_o (i_c + \varepsilon_o \frac{d\phi_E}{dt}$ (Maxwell- Ampere's Circuital law)

History of EM Waves

(1) **Maxwell :** Was the first to predict the EM wave.

(2) **Hertz :** Produced and detected electromagnetic waves experimentally at wavelengths of 6 *m*.

(3) **J.C. Bose :** Produced EM waves of wavelength ranging from 5*mm* to 25 *mm*.

(4) **Marconi :** Successfully transmitted the EM waves up to a few *kilometer*. Marconi discovered that if one of the spark gap terminals is connected to an antenna and the other terminal is Earthed, the electromagnetic waves radiated could go upto several kilometers.

Experimental Setup for Producing EM Waves

Hertz experiment based on the fact that a oscillating charge is accelerating continuously, it will radiate electromagnetic waves continuously. In the following figure

(1) The metallic plates (P_1 and P_2) acts as a capacitor.

(2) The wires connecting spheres S_1 and S_2 to the plates provide a low inductance.

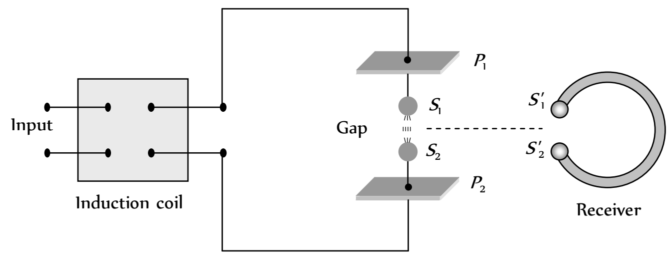


Fig. 30.46

(3) When a high voltage is applied across metallic plates these plates get discharged by sparking across the narrow gap. The spark will give rise to oscillations which in turn send out electromagnetic waves. Frequency of these wave is given by $\nu = \frac{1}{2\pi\sqrt{LC}}$

The succession of sparks send out a train of such waves which are received by the receiver.

Source, Production and Nature of EM Waves

(1) A charge oscillating harmonically is a source of EM waves of same frequency.

(2) A simple *LC* oscillator and energy source can produce waves of desired frequency $\left(\nu = \frac{1}{2\pi\sqrt{LC}}\right)$.

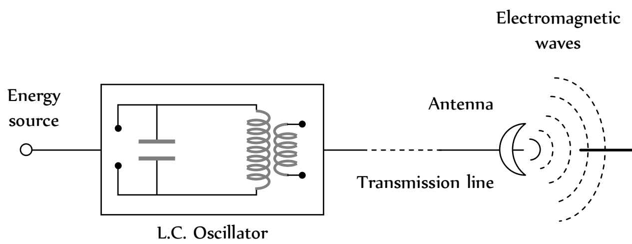


Fig. 30.47

(3) The EM Waves are transverse in nature. They do not require any material medium for their propagation.

Properties of EM Waves

(1) **Speed :** In free space it's speed

$$c = \frac{1}{\sqrt{\mu_0 \varepsilon_0}} = \frac{E_0}{B_0} = 3 \times 10^8 m/s.$$

In medium $v = \frac{1}{\sqrt{\mu\varepsilon}}$; where μ_0 = Absolute permeability, ε = Absolute permittivity.

(2) **Energy :** The energy in an EM waves is divided equally between the electric and magnetic fields.

Energy density of electric field $u_e = \frac{1}{2}\varepsilon_0 E^2$, Energy density of magnetic field $u_B = \frac{1}{2}\frac{B^2}{\mu_0}$

The total energy per unit volume is $u = u_e + u_m = \frac{1}{2}\varepsilon_0 E^2 + \frac{1}{2}\frac{B^2}{\mu_0}$.

Also $u_{av} = \frac{1}{2}\varepsilon_0 E_0^2 = \frac{B_0^2}{2\mu_0}$

(3) **Intensity (I) :** The energy crossing per unit area per unit time, perpendicular to the direction of propagation of EM wave is called intensity.

i.e. $I = \frac{\text{Total EM energy}}{\text{Surface area} \times \text{Time}} = \frac{\text{Total energy density} \times \text{Volume}}{\text{Surface area} \times \text{Time}}$

$\Rightarrow I = u_{av} \times c = \frac{1}{2}\varepsilon_0 E_0^2 c = \frac{1}{2}\frac{B_0^2}{\mu_0}.c\,\frac{Watt}{m^2}$.

(4) **Momentum :** EM waves also carries momentum, if a portion of EM wave of energy u propagating with speed c, then linear momentum $= \frac{\text{Energy}(u)}{\text{Speed }(c)}$

If wave incident on a completely absorbing surface then momentum delivered $p = \frac{u}{c}$. If wave incident on a totally reflecting surface then momentum delivered $-p = \frac{2u}{c}$.

(5) **Poynting vector** $(\vec{S})$. : In EM waves, the rate of flow of energy crossing a unit area is described by the Poynting vector.

(i) It's unit is $Watt/m^2$ and $\vec{S} = \frac{1}{\mu_o}(\vec{E} \times \vec{B}) = c^2\varepsilon_0(\vec{E} \times \vec{B})$.

(ii) Because in EM waves $\vec{E}$ and $\vec{B}$ are perpendicular to each other, the magnitude of $\vec{S}$ is $|\vec{S}| = \frac{1}{\mu_0}E\,B\sin 90^o = \frac{EB}{\mu_0} = \frac{E^2}{\mu C}$.

(iii) The direction of $\vec{S}$ does not oscillate but it's magnitude varies between zero and a maximum $\left(S_{\max} = \frac{E_0 B_0}{\mu_0}\right)$ each quarter of a period.

(iv) Average value of poynting vector is given by

$$\overline{S} = \frac{1}{2\mu_0}E_0 B_0 = \frac{1}{2}\varepsilon_0 E_0^2 c = \frac{cB_0^2}{2\mu_0}$$

The direction of the poynting vector $\vec{S}$ at any point gives the wave's direction of travel and direction of energy transport the point.

(6) **Radiation pressure :** Is the momentum imparted per second pre unit area. On which the light falls.

For a perfectly reflecting surface $P_r = \frac{2S}{c}$; S = Poynting vector; c = Speed of light

For a perfectly absorbing surface $P_a = \frac{S}{c}$.

(7) **Wave impedance (Z) :** The medium offers hindrance to the propagation of wave. Such hindrance is called wave impedance and it is given by $Z = \sqrt{\frac{\mu}{\varepsilon}} = \sqrt{\frac{\mu_r}{\varepsilon_r}}\sqrt{\frac{\mu_0}{\varepsilon_0}}$

For vacuum or free space $Z = \sqrt{\frac{\mu_0}{\varepsilon_0}} = 376.6\,\Omega$.

EM Spectrum

The whole orderly range of frequencies/wavelengths of the EM waves is known as the EM spectrum.

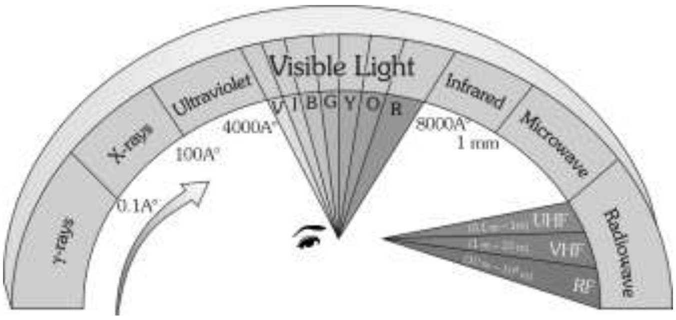


Fig. 30.48

Table 30.2 : Uses of EM spectrum

Radiation	Uses
γ-rays	Gives informations on nuclear structure, medical treatment *etc.*
X-rays	Medical diagnosis and treatment study of crystal structure, industrial radiograph.
UV- rays	Preserve food, sterilizing the surgical instruments, detecting the invisible writings, finger prints etc.
Visible light	To see objects
Infrared rays	To treat, muscular strain for taking photography during the fog, haze etc.
Micro wave and radio wave	In radar and telecommunication.

Earth's Atmosphere

The gaseous envelope surrounding the earth is called it's atmosphere. The atmosphere contains 78% N_2, 21% O_2, and traces of other gases (like helium, krypton, CO_2 etc.)

(1) **Division of earth's atmosphere :** Earth atmosphere has been divided into regions as shown.

(i) Troposphere : In this region, the temperature decreases with height from 290 K to 220 K.

(ii) Stratosphere : The temperature of stratosphere varies from 220 K to 200 K.

(iii) Mesosphere : In this region, the temperature falls to 180 K.

(iv) Ionosphere : Ionosphere is partly composed of charged particles, ions and electrons, while the rest of the atmosphere contains neutral molecules.

(v) Ozone layer absorbs most of the ultraviolet rays emitted by the sun.

(vi) Kennelly heaviside layer lies at about 110 km from the earth's surface. In this layer concentration of electron is very high.

(vii) The ionosphere plays a vital role in the radio communication.

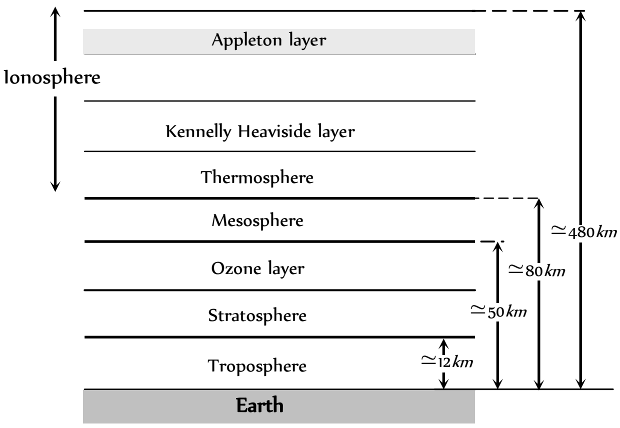


Fig. 30.49

(2) **Green house effect :** The warming of earth's atmosphere due to the infrared radiations reflected by low lying clouds and carbon dioxide in the atmosphere of earth is called green house effect.

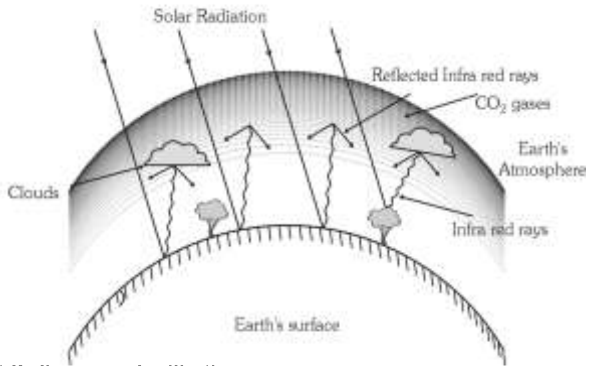


Fig. 30.50

(3

(i) **Radio waves classification**

(a) Very low frequency (VLF) $\rightarrow$ 10 KHz to 30 KHz

(b) Low frequency (LF) $\rightarrow$ 30 KHz to 300 KHz

(c) Medium frequency (MF) or medium wave (MW) $\rightarrow$ 300 KHz to 3000 KHz

(d) High frequency (HF) or short wave (SW) $\rightarrow$ 3 MHz to 30 MHz

(e) Very high frequency (VHF) $\rightarrow$ 30 MHz to 300 MHz

(f) Ultra high frequency (UHF) $\rightarrow$ 300 MHz to 3000 MHz

(g) Super high frequency or micro waves $\rightarrow$ 3000 MHz to 300, 000 MHz

(ii) **Amplitude modulated transmission :** Radio waves having frequency less than or equal to 30 MHz form an amplitude modulation band (or AM band). The signals can be transmitted from one place to another place on earth's surface in two ways

(a) Ground wave propagation : The radio waves following the surface of the earth are called ground waves.

(b) Sky wave propagation : The amplitude modulated radio waves which are reflected back by the ionosphere are called sky waves.

(iii) **Frequency modulated (FM) transmission :** Radio waves having frequencies between 80 MHz and 200 MHz form a frequency modulated bond. T.V. signals are normally frequency modulated.

(4) **T.V. Signals**

(i) T.V. signals are normally frequency modulated. So T.V. signals can be transmitted by using tall antennas.

(ii) Distance covered by the T.V. signals $d = \sqrt{2hR}$

(h = Height of the antenna, R = Radius of earth)

(iii) Area covered $A = \pi d^2 = 2\pi hR$

(iv) Population covered = Area $\times$ Population density.

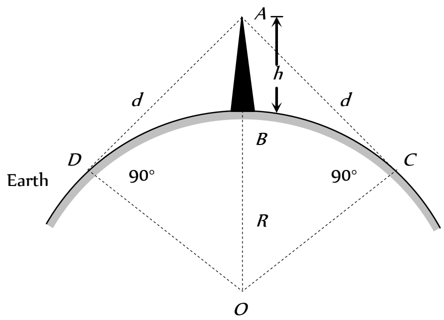


Fig. 30.51

Tips & Tricks

✍ In interference redistribution of energy takes place in the form of maxima and minima.

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

✍ Ratio of maximum and minimum intensities :

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

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

✍ If two waves having equal intensity ($I_1 = I_2 = I$) 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

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

✍ 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 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

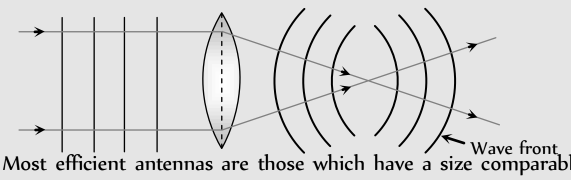
$$\sin\theta = \frac{n\lambda}{d} \qquad \text{(for maximum intensity)}$$

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

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



✍ Most efficient antennas are those which have a size comparable to the wavelength of the of electromagnetic wave they emit or receive.

✍ A substance (like calcite quartz) which exhibits different properties in different direction is called an anisotopic substance.