CHAPTER 9

PHYSICAL OPTICS

* Nature of light is dual:
  1. Particle nature
  2. Wave nature

* Particle Nature : shown in photoelectric effect and Compton shift

* Wave Nature : shown in reflection, rarefaction, diffraction, interference, polarization

* Maxwell showed that light is a form of high frequency electromagnetic waves. The electric and magnetic field vectors are oscillating perpendicular to the direction of propagation of waves.
* Velocity of light, $c = 3 \times 10^8 ms^{-1}$
* Light waves donot require any medium for propagation

* Whenever a wave passes through a certain medium, its particles (particles of medium) are disturbed and execute simple harmonic motion

* WAVE FRONT: The locus of all the points in a medium which have the same phase of vibration.

1. Spherical Wavefront: It is produced by a point source of light

2. Cylindrical Wavefront : When the source of light is linear in shape (such as slit), a cylindrical wavefront is produced.

3. Plane Wavefront : A small part of a spherical or cylindrical wavefront originating from a distant source will appear plane and hence called plane wavefront

* RAYS :
  - → Radial lines leaving the point source in all directions
  - → arrows to indicate direction of wavefronts
  - → Rays are always perpendicular to wavefront

* The distance between consecutive wavefronts is one wavelength.
* Light from the sun reaches the earth with plane wavefront

HUYGEN'S PRINCIPLE

1. Every point of a wavefront may be considered as a source of secondary spherical wavelet, which spreads out in forward direction with the speed equal to speed of propagation of wave.
2. The new position of wavefront after time '$t+\Delta t$' can be found by a drawing a plane tangential to all the secondary wavelets.

* Radius of hemisphere $= c\Delta t$

COHERENT SOURCES

→ The sources which produce waves having the same frequency, equal or comparable amplitude and a constant phase difference are called coherent sources.

→ If the sources send out crests or troughs at the same instant, the individual waves maintain a constant phase difference with one another.

→ The monochromatic sources of light which emit waves, having a constant phase difference are called coherent sources.

→ To get two coherent waves from a point source, one of the following two methods is adopted:

1. Division of wavelength, as in Young's Double slits, Fresnl's byprism and Lioyld's mirror.
2. Division of amplitude by partial reflection and transmission at a boundary as in Newton's rings.

* The points on a Huygen's wavefront which send out secondary wavelet are also coherent sources of light

INTERFERENCE OF LIGHT

* Interference is a superposition of two light waves of same frequency and same amplitude propagating in same medium along same direction very close to each other.
* For constructive interference, light waves reach a point in phase and their path difference $= n\lambda$.
* For destructive interference, light waves reach a point out of phase and their path difference $= (n + 1/2)\lambda$

CONDITIONS OF INTERFERENCE OF LIGHT

1. Monochromatic (having single wavelength)
2. Coherence (having constant phase difference)
3. Same direction
4. Same medium
5. The amplitude of the waves must be equal or nearly equal
6. The path difference of the waves from the two sources must be small.
7. The principle of linear superposition should be applicable.

→ If phase difference between two waves remain constant, then interference pattern will be stationary on screen otherwise it will change continuously.

→ For two ordinary sources, no interference pattern is obtained, bcz the phase changes rapidly and irregularly (that's why to get two coherent waves a single beam of light is split into two or more beams)

CONSTRUCTIVE INTERFERENCE

→ The points in the region of space where the two sets of coherent waves of light meet in phase and reinforce the effect of eachother, constructive interference takes place where brightness is observed on screen.

→ The amplitude of the resultant wave will be greater than either of the individual waves, if they interfere constructively.

→ Phase difference $= 0, 2\pi, 4\pi \ldots$

→ Path different, $d = m\lambda$

$$m = 0, 1, 2, 3 \ldots$$

DESTRUCTIVE INTERFERENCE

→ The points where the two set of waves meet in opposite phase, they cancel the effect of each other and destructive interference takes place due to which dark fringes are observed on screen.

→ The magnitude of the resultant wave will be less than either of the individual waves.

→ Phase differece $= \pi, 3\pi, 5\pi, 7\pi \ldots$

→ Path difference $= \left(m + \frac{1}{2}\right)\lambda$

* Phase Change

$$2\pi = \lambda$$

* Phase Difference δ

$$\delta = \frac{2\pi}{\lambda} \times \text{Path difference}$$

* Principle of Young's Double slit experiment
  Division of wavefront (or wavelength)

* Principle of Interference In A Thin Film
  Division of Amplitude

* Principle of Diffraction Grating
  Interference and Diffraction

* Principle of Michelson's Interferometer
  Division of Amplitude

YOUNG'S DOUBLE SLIT EXPERIMENT

* The point at which wavefront interfere, the straight line to that point show ~~fringe~~ bright fringe.
* When crests fall on crests and trough falls on trough, constructive interference takes place
* When crests fall on troughs, it results in destructive interference.

* Constructive Interference

$$d = m\lambda$$

* Destructive Interference

$$d = \left(m + \frac{1}{2}\right)\lambda$$

d : path difference

* POSITION OF FRINGES ON SCREEN

→ For m^{th} Bright Fringe

$$y = \frac{mL\lambda}{d}$$

L : distance b/w screen and slit

d : distance b/w slit

* The central bright fringe is obtained when $m = 0$
* First order maxima, $m = 1$

→ For m^{th} Dark Fringe

$$y = \left(m + \frac{1}{2}\right) \frac{L\lambda}{d}$$

The first dark fringe will appear for $m=0$ and second dark for $m=1$

* Order Of Bright Fringe

Order $= m$

* Order of Dark Fringe

Order $= m - 1$

* Fringe Spacing

$$\Delta y = \frac{L\lambda}{d}$$

* The distance b.w two consecutive bright or dark fringes is known as fringe spacing
* Distance b.w two dark fringes is the width of light fringe and vice versa
* The bright and dark fringes are of equal width and are equally spaced.

* In Young's double-slit experiment, if the monochromatic source of light is replaced by white light then one sees white central fringe surrounded by a few colored fringes on either side.

INTERFERENCE IN THIN FILM

* A thin film is a transparent medium whose thickness is comparable with the wavelength of light
* Examples : Oil film on water, Soap film, Air film etc
* The principle is based on the division of amplitude by using partial reflection and transmission at the boundary of the two media.
* When exposed to white light, thin film produces colorful pattern due to interference
* When exposed to monochromatic light, only bright and dark fringes are obtained
* Process :
  - → A beam of monochromatic light falls on thin film
  - → Beam is splitted into two parts.
  - → Part 'a' is reflected from upper surface
  - → Part 'b' is reflected from lower surface
  - → The two rays a and b being the same parts of the beam will have phase coherence and are close to eachother so they will superpose each other.
  - → The result of their interference will be detected by eye
* The path of ray 'b' is longer than ray 'a'.
  Their path difference will depend on
  1) Thickness and nature of the film (Refractive Index)
  2) Angle of incidence

* When a wave travels from a medium of lower refractive index (rare medium) to a medium of higher refractive index (denser medium), it undergoes a phase change of 180° (π rad) after reflection.

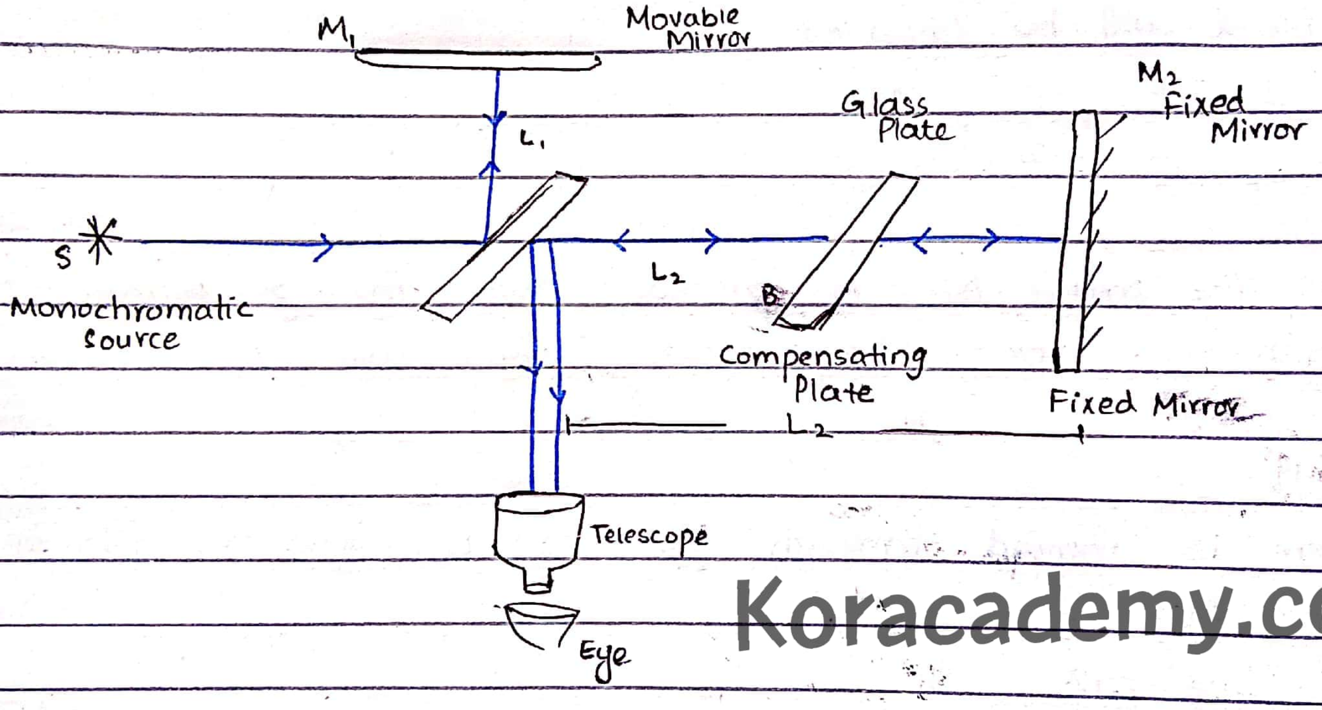
A crest on reflection change into trough

* There will be no phase change in the reflected wave if it travels from a medium of higher refractive index to lower refractive index i-e from denser to rare medium.

A crest remains crest on reflection

MICHELSON'S INTERFEROMETER

* An optical instrument used to study interference of light waves and find its wavelength.
* Principle : Division of amplitude usually by partial reflection and transmission of light at the boundary of the two medium.
* SETUP :



1. Source of monochromatic light
2. Beam splitter (semi-silvered glass plate)
3. Plane mirrors held ⊥ to each other, one is fixed and the other is movable.
4. Micrometer (it is attached to movable mirror)
5. Telescope (to observe interference fringes)

* If the mirror 'M_1' is moved through a distance $\lambda/4$ backward, then the path difference b.w the two beams will be equal to $\lambda/2$ and dark fringe will be seen.

$$d = \frac{\lambda}{4} + \frac{\lambda}{4} = \frac{\lambda}{2}$$

* When mirror M_1 is further moved through distance $\lambda/4$ then the path difference will become 'λ' and now bright band will be observed.

$$d = \frac{\lambda}{2} + \frac{\lambda}{2} = \lambda$$

* Thus as the mirror M_1 is moved slowly through distance $\lambda/4$ each time, bright and dark fringes will appear alternatively.

* If mirror is moved through distance L, and 'm' fringes pass before eye

$$L = \frac{m\lambda}{2}$$

* Interferometer can be used to determine:
    1. Refractive Index
    2. Wavenlength of light

* To Find Wavelength :

$$\lambda = \frac{2P}{m}$$

P : distance through which mirror is displaced

m : no. of fringes

DIFFRACTION OF LIGHT

* Diffraction of light is the phenomenon of bending of light around corners of an obstacle or aperture in the path of light. On account of this, light penetrates into geometric shadow of the obstacle.

* If the size of an obstacle or aperture is comparable with the wavelength of light, light deviates from rectilinear propagation near the edges of the obstacle (or aperture) and enters the geometrical shadow.

* The diffraction effects are appreciable when the dimensions of openings or the obstacles are comparable or smaller than the wavelength of the wave. If the opening or obstacle is large as compared to the wavelength, the diffraction effects are almost negligible.

* In principle, the phenomenon of diffraction is common to all types of waves. In case of sound waves and radio waves, diffraction is observed readily bcz wavelength of these waves is large, and obstacles/apertures of this size are readily available.

* For visible light λ is very small (10^{-9} m). Therefore diffraction of visible light is not so common as apertures of this size are hardly available

* In diffraction pattern, central maximum is of a high intensity and very broad as compared to other maximum.

* Diffraction phenomenon is divided into two types:
  1. Fresnel Diffraction
  2. Fraunhofer Diffraction

* FRAUNHOFER DIFFRACTION AT A SINGLE SLIT

"The diffraction of light produced by a narrow slit when plane light waves are incident normally on the slit and light waves emerging from the slit are also plane, is called Fraunhofer Diffraction"

→ Plane light waves are those light waves that travel / vibrate in a single plane

* In Fraunhofer diffraction, the diffraction pattern is independent of the distance to the screen, depending only on the angles to the screen from the aperture.

* Equation :

$$s = d\sin\theta$$

s : Path difference

d : distance b.w two slits

* Value of $\sin\theta$

→ For $m\lambda$ order minima (Dark fringe)

$$\sin\theta = \frac{m\lambda}{d}$$

→ For secondary maxima

$$\sin\theta = \frac{(m+\frac{1}{2})\lambda}{d}$$

* In optics, Fraunhoffer diffraction equation is used ~~when~~ to model the diffraction of waves when the diffraction pattern is viewed at a long distance from the diffracting object, and also when it is viewed at the focal plane of an imaging lens

MCQ: Which one is diffracted more?

a) Blue ✓c) Red

b) Green d) Violet

Reason: Angle of diffraction is directly proportional to wavelength

V I B G Y O R

→

f decrease

λ increase

DIFFRACTION GRATING

→ To measure wavelength of light accurately
→ A device constructed for this purpose is called grating spectrometer
→ A grating is basically a glass or plastic plate 2 to 3 cm in length and 2 to 3 mm in thickness, on which a large number of parallel, equally spaced slits of the same width are used
→ Monochromatic light is used
→ Achromatic lens is used

* Grating Element ⇒(d) :

Distance b/w two slits is called grating element

$$d = \frac{\text{Unit length of grating}}{\text{Total Number of lines ruled on it}}$$

$$d = \frac{1\ cm}{N}$$

where N is number of lines in one unit length.

* Grating Equation

$$d \sin\theta = m\lambda$$

where $m = 0, 1, 2, 3 \ldots$ and is called order of image

* Resolving Power of Grating

Resolving Power of grating is its ability to separate two wavelengths of light in given order of their spectrum.

$$\text{Resolving Power} = \frac{\lambda}{\Delta\lambda} = Nm$$

N : number of lines ruled on grating
m : order of diffraction
$\Delta\lambda$: difference in two wavelengths to be resolved by the grating

MCQ : A slit of width 'd' is illuminated by red light of wavelength 6500 A°. The first minimum will fall at $\theta = 30°$ if 'd' is :

Sol :

$$d\sin\theta = (m + \tfrac{1}{2})\lambda \quad \text{(For minima)}$$

For first minimum : Order = 0

$$d\sin\theta = \tfrac{1}{2}\lambda$$

$$d = \frac{\tfrac{1}{2}\lambda}{\sin\theta}$$

$$= \frac{2\lambda}{2}$$

$$= \lambda$$

$$= 6500\ A°$$

$$= 6.5 \times 10^{3} \times 10^{-10}$$

$$= 6.5 \times 10^{-4}\ mm$$

DIFFRACTION OF X-RAYS BY CRYSTALS

* X-Rays are electromagnetic waves of very short wavelength of order of 10^{-10} m.
* X-Rays can be diffracted by crystals bcz in crystals the layers of atoms are less than 1nm apart
* It is not possible to produce interference fringes of X-Rays by Young's Double slit experiment or by thin film method.

* The diffration pattern of X-Rays through crystals prove that X-Rays are electromagnetic waves and the atoms are arranged in three dimentional lattices.

BRAGG'S LAW

→ To find wavelength of X-Rays beam by crystal we use Bragg's law

* Expression :

$$2d\sin\theta = m\lambda$$

θ is the glancing angle which is complementary angle to the angle of incidence.

d : path difference

* Using Bragg's law we can determine the interplanar spacing b.w the smaller parallel planes of a crystal, when X-Rays of known wavelength are allowed to diffract from a crystal
* The structure of haemoglobin and double helix structure of DNA has been determined through X-Ray diffraction

POLARIZATION OF LIGHT

* Polarization is the process by which the electric and magnetic vibrations of light waves are restricted to a single plane of vibration.
* Polarization is the property exhibited by transverse waves only. It doesnot occur for longitudenal waves such as sound waves.
* Polarization of light suggests that the light waves are transverse in character.
* Polarized light vibrate only in one plane.

PRODUCTION OF POLARIZED LIGHT:

Polarized light can be obtained from un-polarized light by removing all the waves from the beam except those having vibrations along one particular direction.

This can be achieved by:

1. Selective Absorption
2. Reflection from Surface
3. Refraction through crystals
4. Scattering by tiny particles

* Selective Absorption Method:

→ most common method

→ Polaroid crystal called dichroic substance is used which is made of quinine iodosulphate.

→ Such a crystal transmits all vibrations parallel to its crystallographic axis while absorbs all the remaining vibrations.

* For polarization of light, we perform an experiment with two tourmaline crystals. The light passes through the first crystal parallel to its crystallographic axis and absorbs all remaining vibrations. The transmitted light is known as plane polarized light.

When the second tourmaline crystal is placed such that its crystallographic axis is parallel to first one, then the polarized light will completely transmit through it.

If it is rotated at certain angle, the intensity of transmitted light decrease

When the axis become at right angle to each other, then no light will pass through second crystal

Therefore the second crystal is known as analyzer.

* POLARIZATION BY REFLECTION

When un-polarized light falls on glass, water etc the reflected light is in general partially plane polarized but at a certain angle of incidence called polarizing angle, the polarization is complete. At this angle the reflected ray and the refracted ray in transmitted medium are found to be at right angle to each other.

* Brewster's Law

$$\frac{n_2}{n_1} = \tan i_p$$

n_1 and n_2 are refractive indexes of medium 1 and 2.

For glass of refractive index 1.55, the angle of incidence, $i_p = 57^\circ$

APPLICATIONS OF POLARIZED LIGHT

1. Reducing Glare
   - → In sunglasses; suitably oriented polaroid discs are used to avoid the polarized light
   - → Polaroid discs are placed in front of the camera lens

2. Optical Activity
   - → To find any nutrient concentration in a solution using light
   - → When a beam of light is made to pass through certain crystals (Quartz) or liquids (sugar solution) the direction of vibration of the transmitted polarized light is found to be rotated. This phenomena is called optical activity
   - → For a solution, the angle of rotation depends on its concentration, and an instrument known as polarimeter is used to measure the concentration of the given solution.
   - → In sugar mills, polarimeter is used to measure the sugar conc. in the solution obtained from sugar cane

3. Curtainless Window

Two polarizing sheets are fixed in a window, one inside and the other outside. The inner one is rotated in such a way to adjust the amount of light to be admitted.

4. Control of head light glare

→ During night safe driving is possible if each car having polarized head lights and polarized light viewer.

→ Polarized glasses eleminate the glare of light as it is partly polarized by reflection from water and road.

5. Stress Analysis

When glass, polythene and other plastics are under stress e.g by bending, twisting or uneven heating they become doubly refracting and if viewed in white light b/w two 'crossed' polaroids, coloured fringes are seen around the regions of strain. This effect is called photo elasticity and is used to analyze stresses in plastic model of various structures.

* Refractive index of glass is greater than refractive index of water

* Frequency of light doesnot change when it enters from one medium into another medium

* To obtain greater dispersion by a diffraction grating, the slit separation should be decreased.

* Ultrasonic waves are longitudenal waves and longitudenal waves cannot be polarized.

* Air molecules don't scatter all the ~~molecules~~ colors equally, they scatter the shorter wavelengths (Violet, blue, green) in greater amounts than the longer wavelenc (Yellow, orange, red)

* Refractive index, n

$$n = \frac{\lambda_0}{\lambda}$$

* Refractive Index

The ratio of velocity of light in a vacuum to velocity of light in a specified medium

OR

Refractive index is the ratio of sin of angle of incidence to sin of angle of refraction

$$n = \frac{c}{v} \quad \text{or} \quad n = \frac{\sin \angle i}{\sin \angle r}$$

* rare medium → low refractive index
* denser medium → high refractive index

* As wave travel into denser medium, they slow down and wavelength decreases. and vice versa. Though frequency remains constant

$$c = f\lambda$$

*MCQ: If we use white light in Young's double slit experiment then the colored fringes closer to the central maxima will be:

a) Red ✓b) Blue

c) Green d) Yellow

Greater the wavelength, greater the diffraction and vice versa.

Blue having least wavelength gets least diffracted