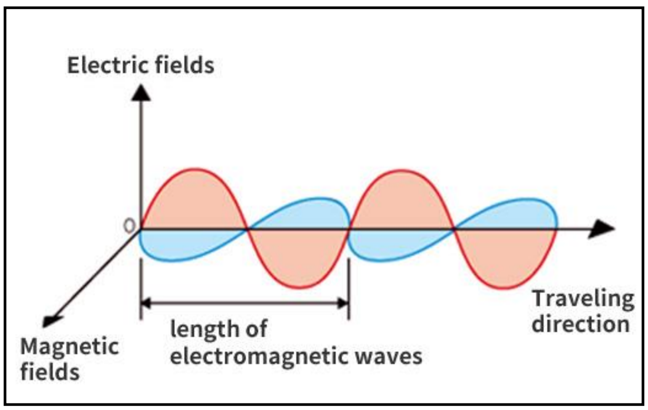
Milestone-1

1. Electromagnetic waves
2. Electromagnetic spectrum
3. Interference of Light
4. Interference in thin parallel film of uniform thickness
5. Interference in wedge shapedfilms
6. Engineering application ofinterference

1. Electromagnetic waves

- An Electromagnetic waves or EM waves are waves that are created as a result of vibrations between an electric field and a magnetic field.
- In other words, EM waves are composed of oscillating magnetic and electric fields. They are hence known as 'electromagnetic' waves.



- An electromagnetic wave can be created by accelerating charges; moving charges back and forth will produce oscillating electric and magnetic fields, and this travel at the speed of light.
- Electromagnetic waves look like light, because they are, and you can see only a tiny portion of them on a large spectrum. They can be visualized as mutually perpendicular oscillating electric fields and magnetic fields. Wavelength is the distance between successive crests of a wavein this case, electromagnetic wave.
- The waves of energy are called electromagnetic (EM) because they have oscillating electric and magnetic fields. The photons are specific units, or packets, of energy. Sometimes those particles interact with each other and change the way the light originally behaved.

Properties of EM Waves

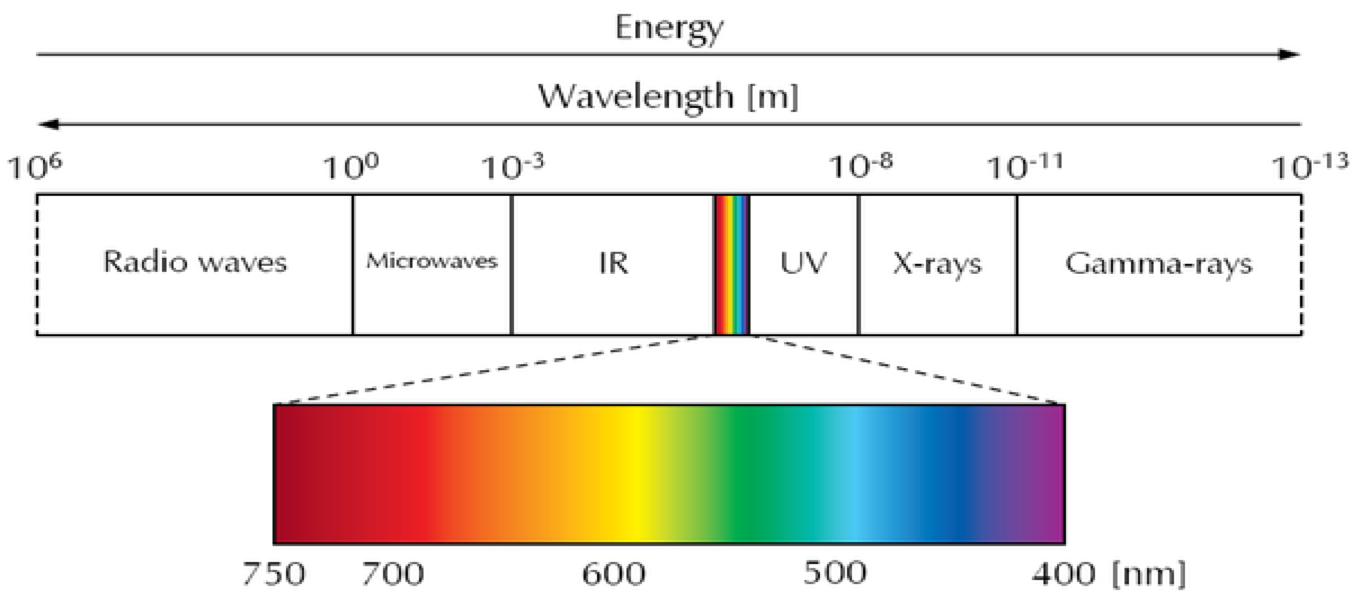
The three properties of electromagnetic waves are-

- EM wave travel at the speed of light.
- It includes ultraviolet waves.

- These waves can transfer energy through empty space.

2. Electromagnetic spectrum

- The electromagnetic spectrum is the term used by scientists to describe the entire range of light that exists. From radio waves to gamma rays, most of the light in the universe is, in fact, invisible to us.
- Light is a wave of alternating electric and magnetic fields.



- The behavior of an electromagnetic wave in a substance depends on its frequency or wavelength.
- The differing behaviors of different groups in the electromagnetic spectrum make them suitable for a range of uses.

Radio waves

- Radio waves are used for communication such as television and radio.
- Radio waves are transmitted easily through the air.
- They do not cause damage if absorbed by the human body, and they can be reflected to change their direction.
- These properties make them ideal for communications.

Microwaves

- Microwaves are used for cooking food and for satellite communications.
- High frequency microwaves have frequencies which are easily absorbed by molecules in food.
- The internal energy of the molecules increases when they absorb microwaves, which causes heating.

- Microwaves pass easily through the atmosphere, so they can pass between stations on Earth and satellites in orbit.

Infrared

- Infrared light is used by electrical heaters, cookers for cooking food, and by infrared cameras which detect people in the dark.
- Infrared light has frequencies which are absorbed by some chemical bonds. The internal energy of the bonds increases when they absorb infrared light, which causes heating.
- This makes infrared light useful for electrical heaters and for cooking food.
- All objects emit infrared light. The human eye cannot see this light, but infrared cameras can detect it.
- This 'thermal imaging' is useful for detecting people in the dark.

Visible light

- Visible light is the light we can see.
- It is used in fiber optic communications, where coded pulses of light travel through glass fibers from a source to a receiver.

Ultraviolet radiation

- Ultraviolet radiation can kill bacteria that are present in the water - this sterilizes the water and makes it safe to drink.
- Ultraviolet radiation is also good for the skin as it helps to make vitamin D. However, too much exposure to UV can cause skin problems.
- Hazards of electromagnetic radiation
- Electromagnetic radiation has many uses, but some of the waves can have hazardous effects, particularly on human body tissues.

Ionizing radiation

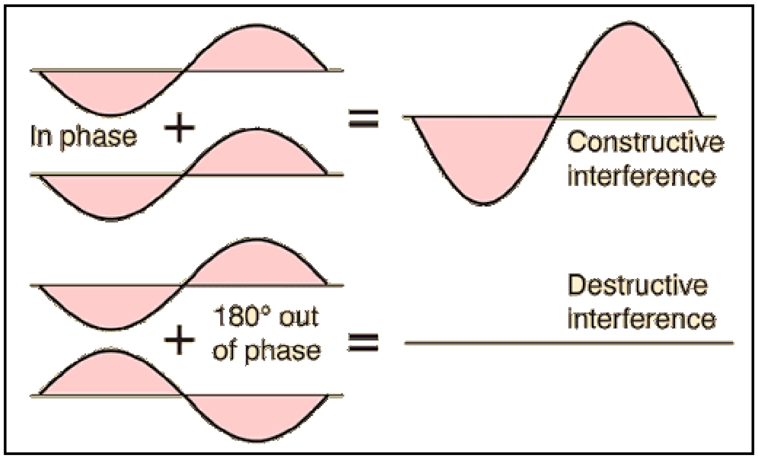
- Ultraviolet waves, X-rays and gamma rays are types of ionizing radiation.
- This means that they can knock electrons from the shells of atoms, turning them into ions.
- This process of ionization can lead tomutations in cells, which can lead to cancer.
- Ultraviolet waves can cause skin to age prematurely and increase the risk of skin cancer.
- Gamma ray scan also damage or kill the cells in a person's body.
- In order to be safe, exposure to ionizing radiation needs to be kept as low as possible, especially for people who work with this type of radiation every day in hospitals.
- A radiographer using X-rays in a hospital has to stand behind a lead shield or be in an other room when the X-ray machine is being operated.

3. Interference of Light

- Interference is the optical phenomenon. In nature many times we can see the interference.

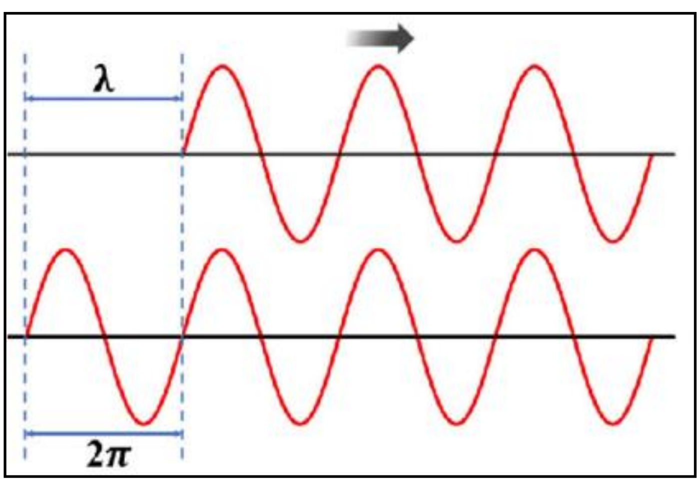
One of the common examples is soap bubble.

- Interference is due to the superposition principle.
- "When two or more wave with constant phase difference, same intensity and same amplitude travelling from medium each wave produces its own displacement irrespective of each other. The resultant of these waves is the vector sum of the amplitude of each wave".
- "The modification or the retribution of intensity of resultant wave due to superposition principle is known as interference".



Constructive Interference

- At certain points waves superimpose in such a way that resultant intensity is greater than the sum of intensities due to individual waves. The interference produced at these points is known as constructive interference.
- i.e. When the crest or trough of one wave coincides with crest or trough of another wave then resultant intensity become maximum and this is constructive interference.
- For constructive interference the two waves must be in phase or having the same phase difference.



- For constructive interference (maxima),Phase difference = 0, 2π, 4π……
- The phase difference of 2π corresponds to the path difference of λ.

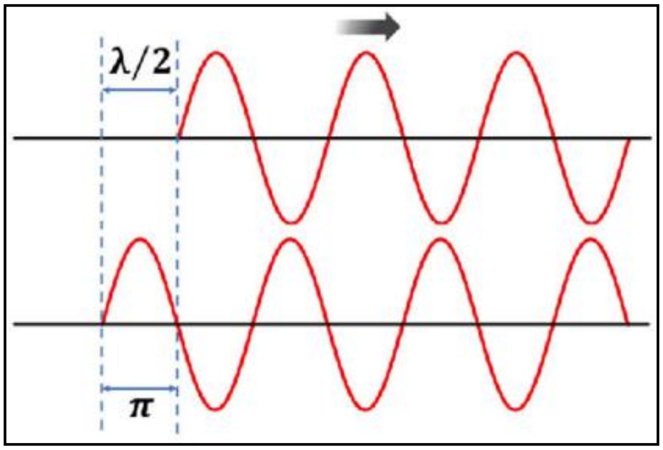
  Path difference = 0, λ, 2λ, 3λ…

  = nλ
- Thus, if the path difference between two waves is an integral multiple of the wavelength,

then it produces the constructive interference or maxima.

Destructive Interference

- At certain points waves superimpose in such a way that resultant intensity is less than the sum of intensities due to individual waves. The interference produced at these points is known as destructive interference.
- When the crest of one wave coincides with trough of another wave then resultant intensity become minimum and this is destructive interference. For destructive interference the two waves must be out phase or having different phase difference.



- For destructive interference (minima),Phase difference = 0, π, 3π, 5π ……
- The phase difference of 2π corresponds to the path difference of λ.
- Path difference $= 0, \frac{\lambda}{2}, \frac{3\lambda}{2}, \frac{5\lambda}{2}...$

$$= (2n \pm 1)\frac{\lambda}{2}$$

- Thus, if the path difference between two waves is an odd integral multiple of half of the wavelength, then it produces the destructive interference or minima.

Condition for Sustained Interference of Light

To obtain well defined interference patterns, the intensity at points corresponding to destructive interference must be zero, while intensity at the point corresponding to constructive interference must be maximum. To accomplish this the following conditions must be satisfied-

- The two interfering sources must be coherent, that is, they must keep a constant phase difference.
- The two interfering sources must be monochromatic. The two interfering sources must emit the light of the same wavelength and time period. This condition can be achieved by using a monochromatic common original source, that is, the common source emits light of a single wavelength.

- The two interfering sources must be of same amplitude,means the amplitudes or intensities of the interfering waves must be equal or very nearly equal so that the minimum intensity would be zero.
- The two interfering sources must be close to each other,means the separation between the two coherent sources must be as small as possible so that the width of the fringes is large and are separately visible.
- The two sources must be narrow or they must be extremely small. A broad source is equivalent to a large number of fine sources. Each pair of fine sources will give its own pattern. The fringes of different interference patterns will overlap.

Methods to Produce Coherent Waves

Division of Wave front

- When light from the source is allowed to pass through two different slits, original wavefront divided into two wavefronts, travel through different paths and when they united, they interfere.
- Examples: Fresnel's bi-prism, Lloyd's mirror.

Division of amplitude

- The incident beam is divided into two or more beams by partial reflection at the surface of thin film.
- The amplitude, and therefore the intensity of the original wavefront, gets divided.
- Examples: Interference in thin film, Newton's rings.

Stokes Relation

- Stokes law states that, a phase change of π or path difference ($\lambda/2$) occurs when light waves are reflected at the surface of the denser medium and no change of phase occurs when light waves are reflected at the surface of a rarer medium.

4. Interference in thin film of uniform thickness

- A film with thickness having few micrometers then such film is thick film. While if the film thickness is of the order of 1 micrometer or nano meter such film is known as a thin film.
- When a thin film of oil spreads on the surface of water and is exposed to white light beautiful colors are seen.

- This phenomenon is also observed when the soap film is illuminated by white light.And can be explained on the basis of interference between light reflected from upper and lower surfaces of thin films.
- Interference due to thin film is due to division of amplitude. When light falls on a thin film some light rays get reflected, refracted and transmitted.
- Thus, to study the interference due to thin film there are two systems A) Reflected System B) Transmitted System.

Interference due thin film in reflectedsystem

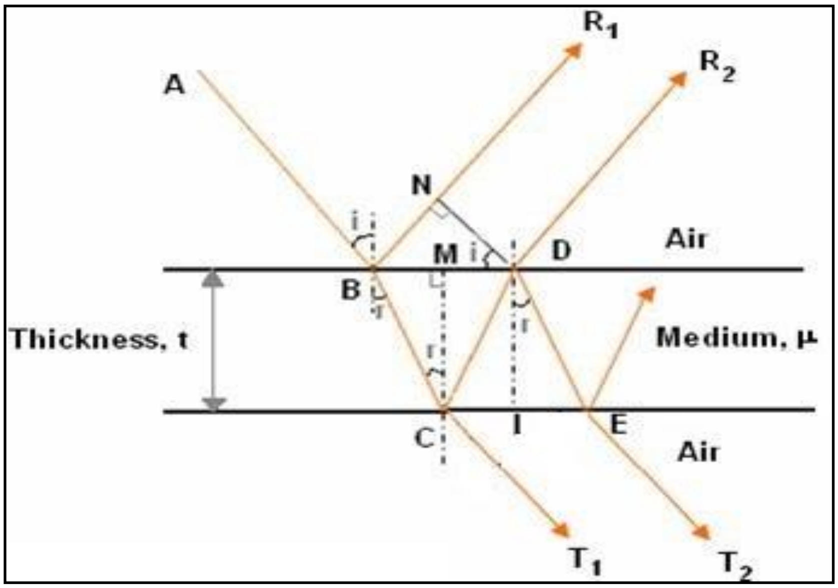


Fig (a)

- Ray AB of monochromatic light having a wavelength (λ) incident on the upper surface of a transparent film of thickness (t) and R.I. (μ) at an angle (i).
- Ray AB is partly reflected along BR_1 and partly refracted along BC at an angle(r).
- The refracted ray BC reflected along CD and finally emerges out alongDR_2.
- BR_1 and DR_2 are derived from the same incident ray, so they are coherent.
- To calculate the path difference between BR_1 and DR_2, construct a perpendicular DN on BR_1 and CM on BD.
- Path of BR_1 and DR_2 beyond DN are same, so the path difference between these two rays is given by,

  Path difference= Δ = Path (BC+CD) in film – Path (BN) in air

  $\Delta = \mu(BC + CD) - BN$--------------------- (1)........(μ_{air}=1)

- Fromfigure(a),

  In ΔBMC,

  $$\cos r = \frac{CM}{BC}$$

  $$BC = \frac{CM}{\cos r} = \frac{t}{\cos r}$$ --(2).......... (CM= t)

In ΔCMD,

$$\cos r = \frac{CM}{CD}$$

$$CD = \frac{CM}{\cos r} = \frac{t}{\cos r} \text{ ---(3)}$$

Put (2) and (3) in (1)

$$\Delta = \mu\left(\frac{t}{\cos r} + \frac{t}{\cos r}\right) - BN \text{ --- (4)}$$

- Again in $\Delta BND, \sin i = \frac{BN}{BD}, \rightarrow BN = BD \sin i$

$$= (BM + MD)\sin i \text{ -- (5)}$$

In ΔBMC,

$$\tan r = \frac{BM}{CM}$$

$$BM = CM \tan r = t \tan r \text{ ---(a)}$$

In ΔCMD,

$$\tan r = \frac{MD}{CM}$$

$$MD = CM \tan r = t \tan r \text{ --(b)}$$

Put (a) and (b) in (5)

$$BN = (t \tan r + t \tan r)\sin i$$

$$BN = 2t \tan r.\sin r \text{ --------------------------- (6)}$$

- Put (6) in(4)

$$\Delta = \mu\left(\frac{2t}{\cos r}\right) - 2t \times \tan r.\sin i$$

Multiply and divide by (sinr) to second term of above equation,

$$= \mu\left(\frac{2t}{\cos r}\right) - 2t \times \left(\frac{\sin r}{\cos r}\right) \times \left(\frac{\sin i}{\sin r}\right) \times \sin r$$

$$= \mu\left(\frac{2t}{\cos r}\right) - 2\mu t\left(\frac{\sin^2 r}{\cos r}\right) \ldots\ldots \left(\frac{\sin i}{\sin r} = \mu\right)$$

$$= 2\frac{\mu t}{\cos r}(1 - \sin^2 r)$$

$$= 2\,\mu t \times \left(\frac{\cos^2 r}{\cos r}\right) \ldots\ldots (1 - \sin^2 r = \cos^2 r)$$

$$\Delta = 2\,\mu t \cos r$$

- Ray BR_1 is reflected from a denser medium to rarer medium, so according to stokes law, additional path difference of $\left(\frac{\lambda}{2}\right)$ or phase difference (п) is introduced.

Total path difference $= 2\,\mu t \cos r \pm \frac{\lambda}{2}$

- **Condition for constructive interference or maxima**:

  For bright point path difference is integral multiple of λ,

  $$2\,\mu t \cos r \pm \frac{\lambda}{2} = n\lambda = 2n\left(\frac{\lambda}{2}\right)$$

  $$2\,\mu t \cos r = (2n-1)\frac{\lambda}{2} \text{.......n=1,2,3, --------- (a)}$$

  $$2\,\mu t \cos r = (2n+1)\frac{\lambda}{2} \text{...... n=0, 1,2, 3, --------- (b)}$$

- **Condition for destructive interference or minima:**

  For dark point path difference is odd multiple of $\frac{\lambda}{2}$,

  $$2\,\mu t \cos r \pm \frac{\lambda}{2} = (2n \pm 1) \times \frac{\lambda}{2}$$

  $$2\,\mu t \cos r = 2n \times \frac{\lambda}{2}$$

  $$= n\lambda ......n = 0,1,2,3.$$

- From (11) and (12), maxima and minima in the interference pattern depends upon two factors,
  1) Thickness of film.
  2) The cosine of angler.
- When t = 0, the film will appear dark and as the thickness is increased, maxima and minima occur alternatively.

Interference due thin film in transmittedsystem

In transmitted system ray CT_1 and ET_2 are consider for superposition to get the interference.

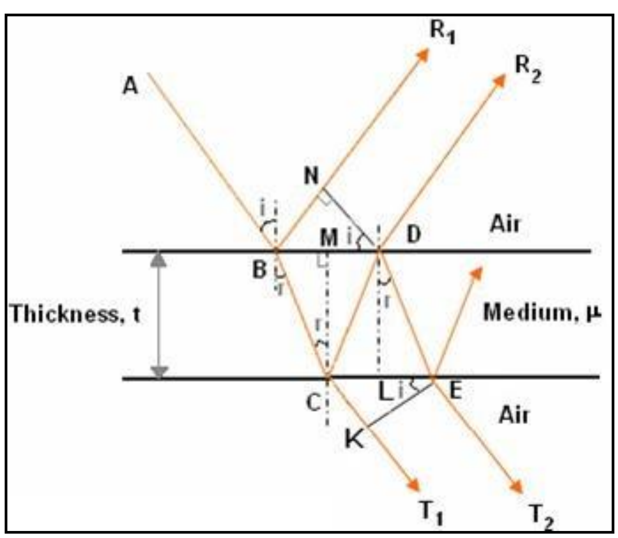


Fig (b)

Total path difference between transmitted rays CT_1 and $ET_2 = \Delta = 2\,\mu t \cos r$

The term $\frac{\lambda}{2}$ is not added, because reflection at D is in the same denser medium from reflecting surface. Thus, stokes law is not applied.

- **Condition for constructive interference or maxima**:

  $2\,\mu t \cos r = 2n \times \frac{\lambda}{2}$

  $= n\lambda$ ....n=0,1,2,3.

- **Condition for destructive interference or minima**:

$2\,\mu t \cos r = (2n \pm 1) \times \frac{\lambda}{2}$

- As the constructive interference condition in the reflected system becomes destructive interference conditions in transmitted light, the reflected and transmitted systems are complimentary.

5. Interference in wedge shaped films

- An arrangement of two surfaces in contact with each other at one point and gradually increasing the thickness at other is known as wedge shaped thin film as shown in figure (c)

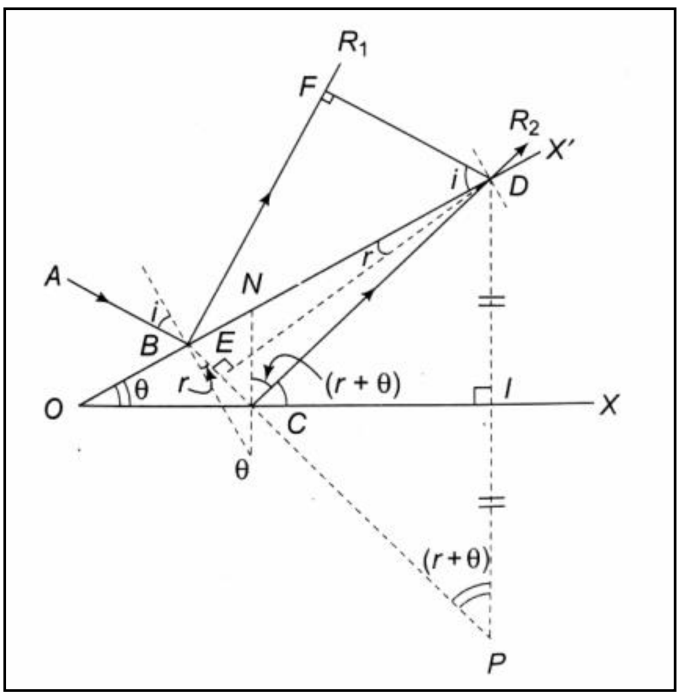


Fig (c)

- From fig. path difference between BR_1 and DR_2 is

$\Delta = \mu_{film}(BC + CD) - BF\ldots\ldots(\mu_{air} = 1)$

Total path difference is given by

$\Delta = 2\,\mu t\cos(r+\theta) \pm \frac{\lambda}{2}$ Angle BCN= (r+ ϴ) due to exterior angle property in geometry.

- **Condition for constructive interference or maxima:**

$2\,\mu t\cos(r+\theta) \pm \frac{\lambda}{2} = 2n \times \frac{\lambda}{2} = n\lambda$ ....n = 0, 1, 2, 3, ...

$2\,\mu t\cos(r+\theta) = (2n \pm 1)\frac{\lambda}{2}$

- **Condition for destructive interference or minima**:

$2\,\mu t\cos(r+\theta) \pm \frac{\lambda}{2} = (2n \pm 1) \times \frac{\lambda}{2}$

$2\,\mu t\cos(r+\theta) = 2n \times \frac{\lambda}{2} = n\lambda \ldots n = 0,\ 1,\ 2, 3.$------

- **Fringewidth**
- Fringe width is defined as "The separation between two successive bright or dark fringes".

$$\omega = \frac{\lambda}{2\mu sin\theta}$$

- For very small angle $\sin\theta \approx \theta$,

$\omega = \frac{\lambda}{2\mu\theta}$,

This is the expression for fringe width for any medium.

- For air, μ=1

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

7. Formation of colours in thin film

- According to interference phenomenon, when thin film of soap bubble, or an oil film on water or wedge-shaped air film between two glass plates interacted with light beautiful colours spectrum is seen in reflected light. This colour formation is due to interference was first observed byYoung.
- When white light interacts with film, light reflected from top and bottom surfaces of the film, then these rays interfere with each other and produce interference pattern of coloured fringes.
- The path difference between these rays depends upon thickness(t) of filmand angle of refraction(r) of thefilm.
- Due to constructive interference, some colours satisfied the condition of maxima

$2\,\mu t\cos r = (2n \pm 1)\frac{\lambda}{2}$ and will be visible with maximum intensity.

- While other colors satisfy condition of minima i.e $2\mu t\cos r = n\lambda$, will be absent from the reflected system.
- Similarly, if a point is observed at a different angle by keeping the same thickness or different

points at different thickness, a different set of colors is observed at each time.

- The colors visible in reflected system will be complementary to the colors visible in transmitted system.

8. Engineering application ofinterference:

Testing of optical flatness of surface

- This is one of the most important practical applications of interference which is used to determine optical flatness of a glass plate.
- The plate (OB) whose optical flatness is to be determined placed on another plate (OA) which is totally flat.

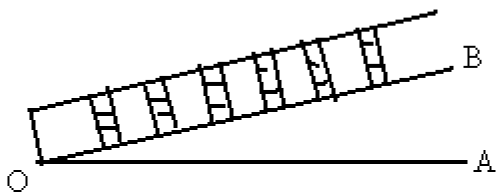


Fig (d)

- In between plate OA & OB the thin air film of different thickness is produced.
- When monochromatic light incident on this combination of plate OA & OB then we get alternate dark and bright fringes in the field of view of travelling microscope.
- If the fringes are of equal thickness then we can say that OB is optically flat.
- If not, then polish the surface OB & then observed fringes, when we get fringes of equal thickness then that plate OB is said to be optically flat shown in fig (d).

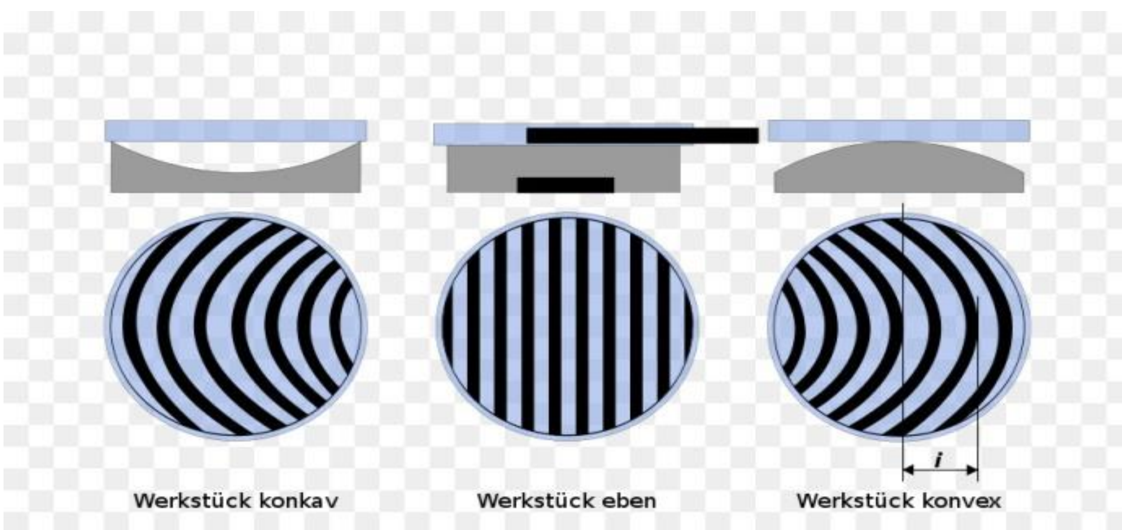


Fig (e)

- If the interference pattern is not having vertical bands the surface is not flat as shown in above figure shown in fig (e)

➢ Non-reflecting /Anti-reflecting coating (AR):

- When light falls on camera then some light gets reflected back it decreases the quality of image.

- Thus, it is necessary to reduce the reflection to improve quality of an image.
- The anti-reflection coating is used in cameras, projector lens, telescopes etc, to reduce loss of light by reflection.

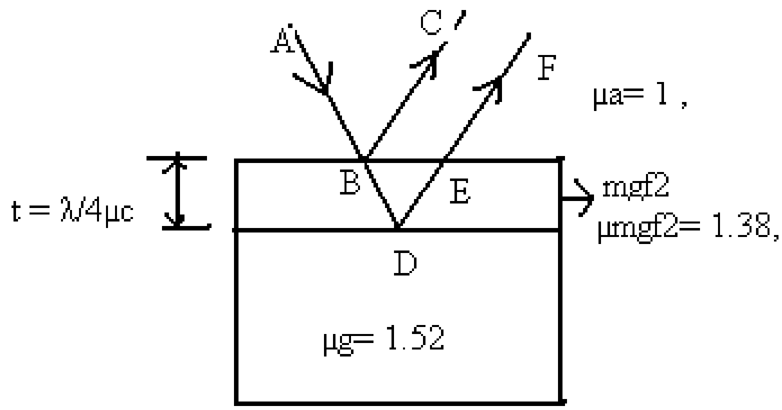


Fig (f)

- When light falls on camera it gets reflected from upper and lower surfaces of an anti-reflecting coating as shown in above figure fig (f).
- Ray BC (ray 1) is reflected from surface of coating ray and ray EF (ray 2) reflected from the surface of the lens.
- To reduce the reflection the ray 1 and ray 2 must produce the destructive inference.
- So, the thickness of the anti-reflecting coating is chosen such that after reflection the ray 1 and ray 2 are in out of phase to produce destructive interference.
- So, the path difference between reflected rays is $\frac{\lambda}{2}$ or phase difference π (destructive interference)
- Due to destructive interference the intensity of reflected rays reduced and thus reflections can be minimized.
- The condition for minima is,

$$2\mu_c t \cos r = \frac{\lambda}{2}$$

$$2\mu_c t = \frac{\lambda}{2} \text{............ (for r=0, cosr =1),}$$

$$t = \frac{\lambda}{4}\mu c$$

- Thus, the thickness of anti-reflecting coating can be determined by the above formula.
- There are different materials are available for anti-reflecting coating. But for by considering the wavelength of light ($5500A^0$) the most common AR coating used are

magnesium fluoride and cryolite. The Refractive index of Mgf_2 i.e. μ_{mgf2}=1.38 while for cryolite it is $\mu_{Na3AlF6}$ =1.36

μ_a= 1, μ_{Mgf2}= 1.38, μ_g=1.52

- By adjusting thickness, $t = \frac{\lambda}{4}$, condition for destructive interference being satisfied, it gives no light in the reflected system.

Steps and formula

Problem Based on Interference of light

Interference in thin parallel films:

Reflected light

- $2\mu t \cos r = (2n-1)\times\frac{\lambda}{2}$, (For maxima or bright fringe), wheren=1,2,3,4……
- $2\mu t \cos r = n\lambda$ (For minima or dark fringe)

Transmitted light:

- $2\mu t \cos r = n\lambda$ (for maxima or bright fringe)
- $2\mu t \cos r = (2n-1)\times\frac{\lambda}{2}$ (For minima or dark fringe)

$$\mu = \left(\frac{\sin i}{\sin r}\right)$$

Fringe width:

$$\omega = \frac{\lambda}{2}\mu\theta,$$

Wedge shaped film:

Reflected light

- Condition of maxima, $2\mu t \cos(r+\theta) = (2n-1)\times\frac{\lambda}{2}$
- Condition of minima, $2\mu t \cos(r+\theta) = n\lambda$

Transmitted light:

- Condition of maxima, $2\mu t \cos(r+\theta) = n\lambda$
- Condition of minima, $2\mu t \cos(r+\theta) = (2n-1)\times\frac{\lambda}{2}$

EXERCISE-1.1

Q.1 Derive the conditions for maxima and minima due to interference of light reflected from thin film of uniform thickness.

Q.2 Derive P.D between reflected rays when monochromatic light of wavelength λ falls with angle I on uniform thickness of film of R.I μ. Write condition of maxima & minima.

Q.3 Why do we see beautiful colours in thin film when it is exposed to sunlight?

Q.4 Explain any one application of interference.

Q.5 Write a short note on anti-reflection coating.

Q.6 Write a short note on electromagnetic waves.

Q.7 Explain electromagnetic spectrum.

Q.8 A parallel beam of sodium light strikes a film of oil floating on water, when viewed at an angle of $30°$ from the normal, eighth dark band is seen. Determine thickness of the film. RI of oil is 1.46, $\lambda = 5890A°$

Q9 A parallel beam of monochromatic light of wavelength $\lambda = 5890A°$ is incident on a thin film of $\mu = 1.5$ such that the angle of refraction is $60°$. Find minimum thickness of film so that it appears dark. For normal incidence, what is the thickness required?

Q.10 A soap film having refractive index 1.33 and thickness $5 \times 10^{-5}cm$ is viewed at an angle of $35°$ to the normal. Find wavelength of light in the visible spectrum which will be absent from reflected light.

Q.11 Fringes of equal thickness are observed in a thin glass wedge of refractive index 1.52. The fringes spacing is 1 mm and wavelength of light is $5893A°$, calculate the angle of wedge in seconds of an arc.

Q12. A beam of monochromatic light of wavelength 5.82×10^{-7} mfalls normally on a glass wedge of wedge angle 20 second of an arc. If the refractive index of a glass is 1.5. Find number of interference fringes per centimeter of the wedge length.

Q.13 A glass of refracting index 1.5 is to be coated with a transparent material of refractive index 1.2, so that the reflection of light of wavelength $6000A°$ is eliminated by interference. What is required thickness of the coating?

Milestone-2

1. Diffraction of light
2. Diffraction at a single slit
3. Plane Diffraction grating
4. Fraunhofer diffraction at a circular aperture
5. Rayleigh's criterion for resolution
6. Resolving power of telescope and grating

1. Diffraction of Light

- The word 'diffraction' is derived from the Latin word "diffractus" which means a break to piece. "The phenomenon of bending of light round the corners of an obstacle and resulting into geometrical shadow (of an object) is called diffraction".

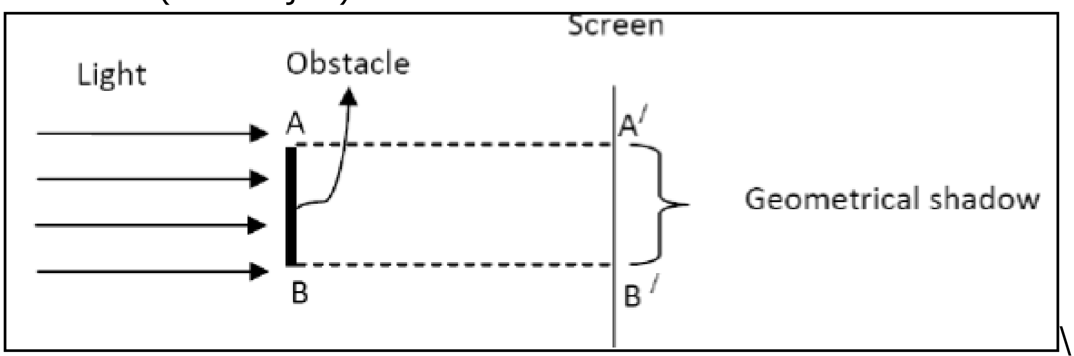


Fig (1)

- "The distribution of light intensity in dark and bright fringes (i.e. alternate maxima and minima) is known as diffraction pattern."

The diffraction may be divided into two groups

Fraunhofer diffraction

- The diffraction in which,the distance between source and screen is infinite from the diffracting element is called Fraunhofer diffraction.
- So, a pair of lenses is required in this diffraction. One is to convert that all light into a parallel beam coming from a source to obstacle and other to focus the parallel diffracted rays on a screen.

Fresnel diffraction

- The diffraction in which, the distance between source and screen is finite from a diffracting element is called Fresnel diffraction.
- Due to finite distance, lenses are not required in this diffraction.

Distinguish between fraunhofer and Fresnel diffraction

Fraunhofer diffraction	Fresnel diffraction
Source and screen are at infinite distance from diffracting element.	Source and screen are at finite distance from diffracting element.
A pair of biconvex lenses is required.	No lenses are required.
Incident wavefront is plane wavefront.	Incident wavefront is either spherical or cylindrical.
The diffracted wavefront is plane.	The diffracted wavefront is spherical or cylindrical.
It has many applications in designing optical instruments.	It has less application in designing optical instruments.
Maxima and minima are well defined.	Maxima and minima are not well defined.

2. Fraunhofer diffraction due to single slit

- To observe fraunhofer diffraction at the single slit, source of light (s) is kept at the focus of a biconvex lens(L) to convert diverging light into a parallel beam.
- Another biconvex lens (L′) is placed beyond slit to focus parallel diffracted rays on a screen placed in focal plane of lens.
- Let a parallel beam of light having wavelength (λ) incident normally on slit AB of width (a).
- According to Huygens principle every point on slit act as a secondary source of light and it emit secondary waves.
- When these secondary rays travel without any deviation and focus at point C on the screen. As these rays have no path difference, point C is principal maxima having maximum intensity.

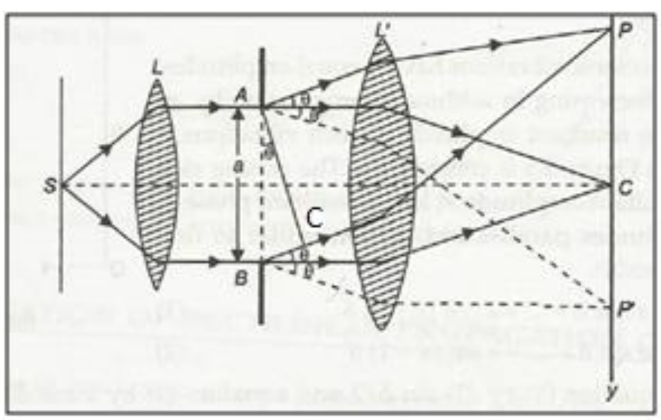


Fig (2)

- When these secondary rays travels with a deviation angle (θ), focus at point P and P′ on screen as shown in figure (2).
- Intensity of point P and P′ on the screen depends on the path difference between the first and last secondary rays reaching to that point.
- To find the path difference, consider the slit AB is divided into N number of pseudo parallel slits having width Δx as shown figure (3).

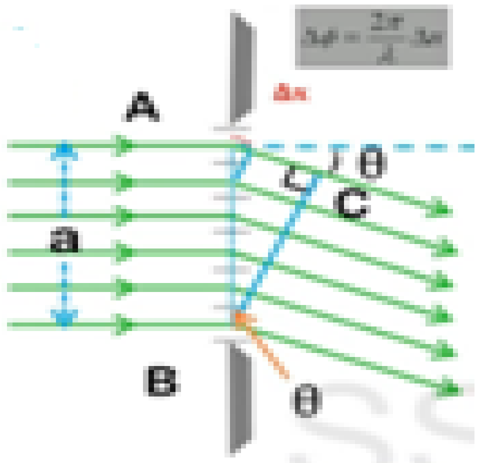


Fig (3)

- Thus, slit width (a) $= \Delta x_1 + \Delta x_2 + \Delta x_3 + \cdots + \Delta x_N$
- From figure (3) in ΔABC,

$$\sin\theta = \frac{AC}{AB}$$

$$AC = AB\sin\theta$$

Path difference, $\Delta = \Delta X \sin\theta$ .... (1)

- The phase difference $\phi = \frac{2\pi}{\lambda}$ x (Path Difference)
- The phase difference $\Phi = \frac{2\pi}{\lambda} \times (\Delta X \sin\theta)$ .... (2)
- Therefore,

  Path difference $= \Delta x \sin\theta$

  Total path difference $= a\sin\theta$
- Total Phase difference, $\Phi = \frac{2\pi}{\lambda} \times (a\sin\theta)$
- For simplicity, $\alpha = \frac{\phi}{2} = \frac{\pi}{\lambda}(a\sin\theta)$.. (3)
- The amplitude of vibration of a wave from each small slit is same and so represented by a small vector known as a phasor.
- There are 'N' phasor of the same amplitude and the same phase difference.
- The (N) phasors of equal amplitude and same phase difference between adjacent phasors form an arc of a circle (PQ) with centre (O) & radius(R) as shown in figure (4).
- The length of arc (PQ) represent maximum amplitude (E_m), obtained by adding the phasors without any phase difference between them.
- Now consider the phasor which are deviated by an angle θ having phase difference of $d\phi$. Thus the maximum amplitude E_m which is the length of an arc in figure (4).

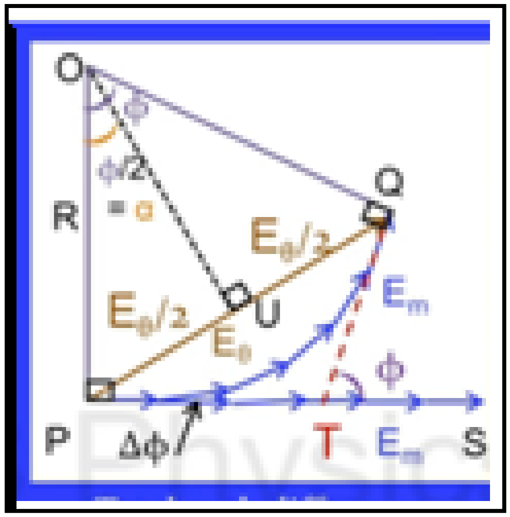


Fig (4)

- The PQ is the chord of a circle and it shows the resultant amplitude E_θ.
- Draw a perpendicular form apex angle ϕ on PQ; it will bisect the chord as well as apex angle.
- Therefore in Δ OUP,
- $\sin(\phi/2) = \frac{PU}{OP} = \frac{\frac{E_\theta}{2}}{R}$

$\sin\alpha = \frac{E_\theta}{2R}$ ------------------------------------(From (3))

$E_\theta = 2R\sin\alpha$ .... (4)

Now, if ϕ is the angle, R is radius and E_m is the length of arc, then

$\phi = \frac{\text{Length of arc}}{R} = \frac{E_m}{R}$.

$E_m = R\phi = 2R\alpha$ -------------------------- (From (3))

$E_m = 2R\alpha$ .... (5)

Divide equation (4) by (5),

$$\frac{E_\theta}{E_m} = \frac{2R\sin\alpha}{2R\alpha} = \frac{\sin\alpha}{\alpha}$$

$E_\theta = E_m\left(\frac{\sin\alpha}{\alpha}\right)$ .... (6)

Equation (6) gives the resultant amplitude due to single slit.

We have the relation; intensity is directly proportional to the square of amplitude.

Thus, $I_\theta \alpha E_\theta^2$, Where I_θ is the resultant intensity due to single slit.

$$I_\theta = E_m^2\left(\frac{\sin\alpha}{\alpha}\right)^2$$

$I_\theta = I_m\left(\frac{\sin^2\alpha}{\alpha^2}\right)$ .... (7)

Where, $I_m = E_m^2$

Video link for this derivation

Principal maxima

The resultant amplitude due to single slit is,

$$E_\theta = E_m\left(\frac{\sin\alpha}{\alpha}\right)$$

$$=\left(\frac{E_m}{\alpha}\right)\left[\alpha-\left(\frac{\alpha^3}{3!}\right)+\left(\frac{\alpha^5}{5!}\right)-\left(\frac{\alpha^7}{7!}\right)+\cdots\right]$$

$$=E_m\left[1-\left(\frac{\alpha^2}{3!}\right)+\left(\frac{\alpha^4}{5!}\right)-\left(\frac{\alpha^6}{7!}\right)+\cdots\right]$$

$$=E_m\left[1-\left(\frac{\alpha^2}{3!}\right)+\left(\frac{\alpha^4}{5!}\right)-\left(\frac{\alpha^6}{7!}\right)+\cdots\right]$$

For principal maxima, $E_\theta = E_m$

So, $\alpha = 0$

But, $\alpha = \frac{\phi}{2} = \frac{\pi}{\lambda}(a\sin\theta)$

As $a \neq 0, \sin\theta = 0,$

When, $\theta = 0$

For $\theta = 0$ and $\alpha = 0$ value the resultant intensity is maximum at C and is known as principal maximum.

Minimum intensity (minima)

For minima the intensity at P or P' will zero.

For this, sin α =0

Sin α =0 =sin (±mπ)

α = ±mπ, m = 1, 2,3,4,------

$$\alpha = \frac{\phi}{2} = \left(\frac{\pi}{\lambda}\right)a\sin\theta = \pm m\pi$$

$$a\sin\theta = \pm m\lambda$$

Therefore points of minimum intensity lies on either side of principal maxima.

Secondary maxima

The condition for secondary maxima is given by,

$$\alpha = \pm\left(m+\frac{1}{2}\right)\pi, m = 1,2,3\ldots$$

$$I_\theta = I_m\left(\frac{\sin\alpha}{\alpha}\right)^2$$

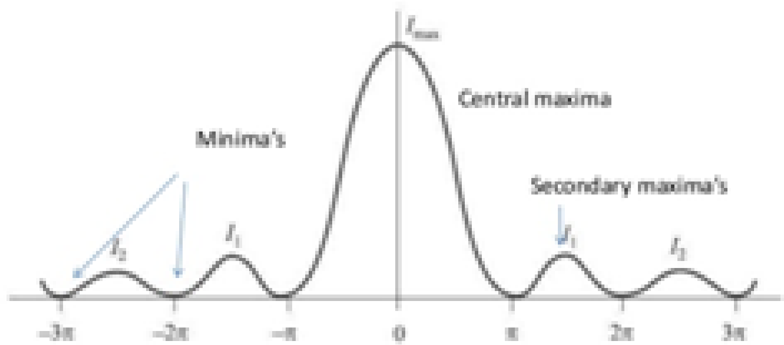
$$\frac{I_\theta}{I_m} = \left[\frac{\left\{ \sin\left(\frac{m+1}{2} \right) \pi \right\}}{\left\{ \left(\frac{m+1}{2} \right) \pi \right\}} \right]$$

m = 1,2,3-------

= 0.045, 0.016, 0.0083------

This shows that intensity of secondary maxima decreases rapidly.

Intensity distribution of diffraction pattern due to single slit



- The diffraction pattern due to single slit consists of bright central maximum and on both sides having alternate minima of zero intensity and secondary maxima of decreases intensities.

3. Plane diffraction grating (N slits diffraction)

- A plane diffraction grating is an arrangement of large number of close, parallel, straight, transparent and equidistant slits each of equal width (a) with neighboring slits being separated by an opaque region of width (b).
- The light cannot pass through lines drawn by diamond.
- There are about 15,000 lines per inch on such a grating to produce diffraction of visible light.
- The spacing (a+b) between centre of adjacent slits is known as a grating element.

Theory of plane diffraction grating

Step 1:

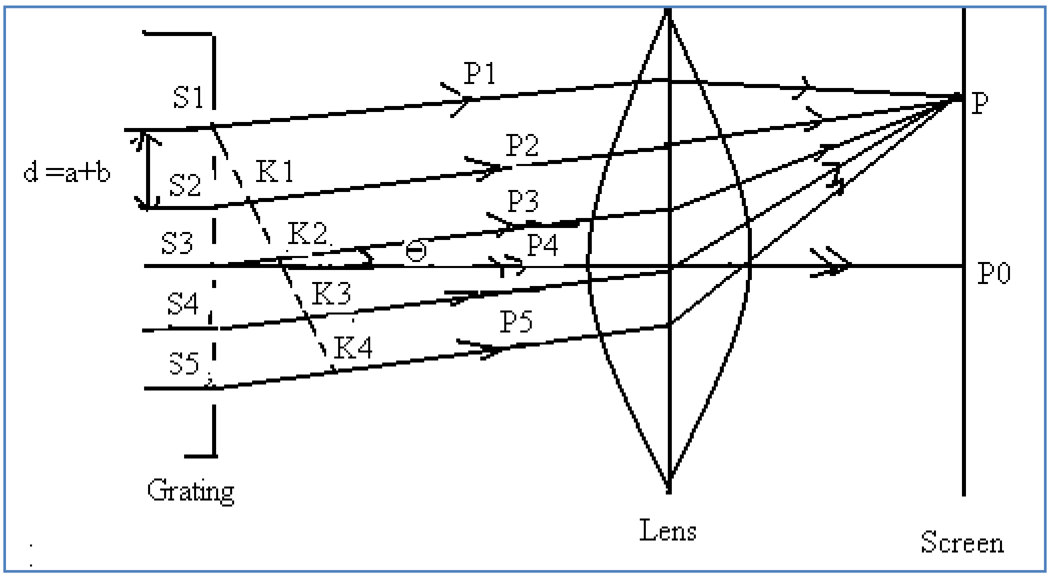
- Consider plane diffraction grating having (N) number of slits each of width (a) & separated by opaque space (b).
- The distance between centres of the adjacent slit is (a+b) known as a grating element.
- When a plane wavefront of monochromatic light incident normally on a grating, every point in each slit acts as a source of secondary wavelets and sends in all directions.
- The secondary wavelets travelling along incident light are brought to focus at a point (P_0) on screen.
- The rays which diffracted through an angle (Θ) incident at point P on screen & now we want to calculate resultant intensity at point P.

Step 2:

- Resultant amplitude due to single slit is given by,

$$E_\theta = E_m\left(\frac{\sin\alpha}{\alpha}\right) \qquad \text{Where, } \alpha = \left(\frac{\pi}{\lambda}\right)(a\sin\theta)$$

- All secondary wavelets replaced by a single wave of amplitude $\left[Em\left(\frac{\sin\alpha}{\alpha}\right)\right]$ starting from mid-point of slit.
- Let S_1, S_2, S_3-------S_N be mid points of N slits.



Step 3:

Therefore, path difference between S_1P_1 & $S_2P_2 = S_2K_1 = (a+b)\sin\theta$

And Phase difference in $S_1P_1 \& S_2P_2 = \Delta\phi = \left(\frac{2\pi}{\lambda}\right)(a+b)\sin\theta$

Similarly, path difference between $S_3P_3 \& S_1P_1 = S_3K_2 = 2(a+b)\sin\theta$

And Phase difference in $S_3P_3 \& S_1P_1 = 2\Delta\phi = \left(\frac{2\pi}{\lambda}\right)2(a+b)\sin\theta$

therefore $\Delta\phi = \left(\frac{2\pi}{\lambda}\right)(a+b)\sin\theta$

therefore, phase difference between adjacent vibration being constant equal to

$$\Delta\phi = \left(\frac{2\pi}{\lambda}\right)(a+b)\sin\theta$$

Step 4:

From vector addition method, resultant amplitude given by

$$E_\theta = Em \times \left(\frac{\sin\alpha}{\alpha}\right)\left(\frac{\sin N\beta}{\sin\beta}\right)$$

The resultant intensity is given by,

$$I_\theta = I_m\left[\left(\frac{\sin\alpha}{\alpha}\right)^2\right]\times\left[\left(\frac{\sin N\beta}{\sin\beta}\right)^2\right], \qquad \text{Where} \quad \beta = \frac{\pi}{\lambda}\times(a+b)\sin\theta$$

Step 5:

Principal maxima

1) The resultant intensity of light at point P is given by, $\sin\beta = 0$

Or $\beta = \pm m\pi \quad m=0,1,2,3,$ ------

But for these values, $\left(\frac{\sin N\beta}{\sin\beta}\right)$ becomes indeterminate.

2) Hence taking limits as $\beta = \pm m\pi$

$$\lim_{\beta = \pm m\pi}\left(\frac{\sin N\beta}{\sin\beta}\right) = \lim_{\beta = \pm m\pi} d\frac{(\sin N\beta)}{d(\sin\beta)}$$

$$= \lim_{\beta = \pm m\pi}\frac{N\cos N\beta}{\cos\beta}$$

$$= \lim_{\beta\to\pm m\pi}\frac{N\cos Nm\pi}{m\pi}$$

Put $m=0$ & $\cos 0 = 1$

$$\lim_{\beta = \pm m\pi}\left(\frac{\sin N\beta}{\sin\beta}\right)^2 = N^2$$

Therefore $I_\theta = I_m \times N^2\left[\left(\frac{\sin\alpha}{\alpha}\right)^2\right]$

$I_\theta = N^2 *$ intensity due to single slit.

As $\beta = \pm m\pi$

$$\frac{\pi}{\lambda}\times(a+b)\sin\theta = \pm m\pi$$

$(a+b)\sin\theta = \pm m\lambda \qquad m= 0,1,2,3,$ ------

Where m= order of spectrum.

Minima

Intensity is minimum when sinNβ =0 but sinβ ≠0 and m can have all integral values except 0,N,2N,3N-------nN because for that we get principal maxima.

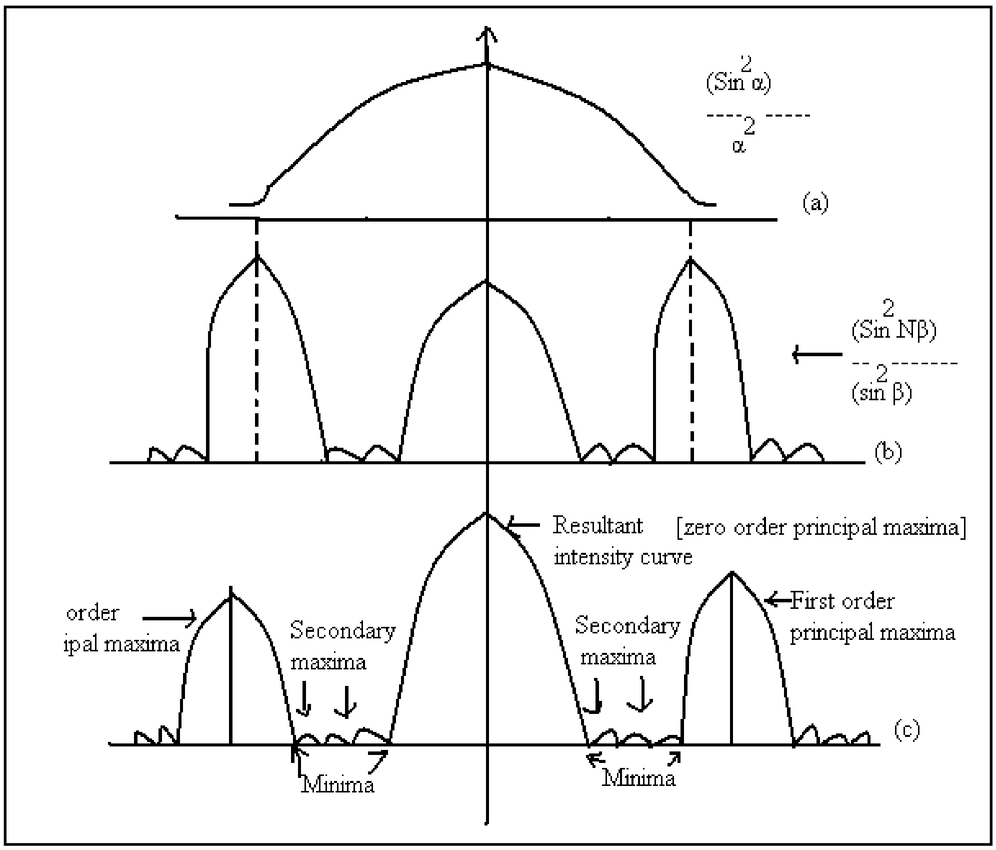
$$N\beta = \pm m\pi$$

$$N\frac{\pi}{\lambda}\times(a+b)\sin\theta = \pm m\pi$$

$$N(a+b)\sin\theta = \pm m\lambda$$

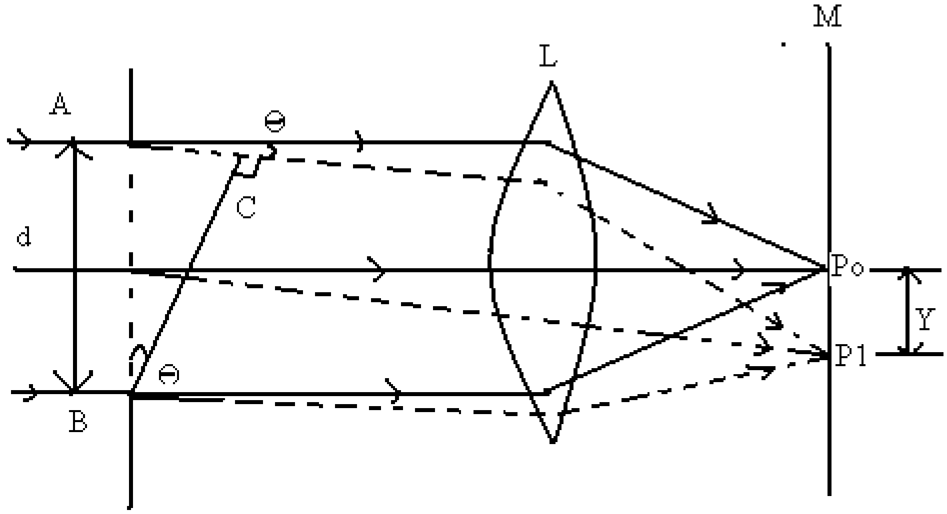
Step 6:

Intensity distribution



4. Fraunhofer diffraction ata circular aperture

- Let us consider a circular aperture of diameter (d)
- A plane wave front incident normally on this aperture AB.
- So, each and every point of wavefront on the circular aperture will acts as a source of secondary wavelets.
- These waves spread in all directions and all diffracted beam be focused on screen by aconvex lens (L).



- The waves which are travelling normal to the circular aperture are focused at point P_0 & shows maximum intensity due to same phase difference in all waves.
- Now the waves travelling at an angle Θ with respect to the normal. So, all these waves meet at point P_1 on screen. Assume $P_0P_1 = Y$
- So, the path difference between waves from A & B reading P_1 is given by AC.

  In Δ ABC,

  $$\sin\theta = \frac{AC}{AB} = \frac{AC}{d}$$

  $$AC = d\sin\theta$$
- In comparison with single slit diffraction the point P_1 will be of minimum intensity for integral multiple of wavelength (λ) i.e. path difference is mλ and for maximum intensity the path difference is odd multiple of $\frac{\lambda}{2}$.
- For minima, mathematically

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

  and for maxima $d\sin\theta = (2m+1)\frac{\lambda}{2}$, Where m = 1, 2,3, ------
- As point (P_1) is at minimum intensity, then all other points are geometrically at the same distance from point P or P_1. Therefore, every point lying on circular structure of radius (r) which has minimum intensity.
- This diffraction pattern is just like rotating the intensity distribution graph of single slit diffraction above central axis passing through P which traces the circular aperture perfectly symmetrical.
- The point P produces circular ring of uniform intensity.
- This produces a diffraction pattern due to circular aperture produces central bright disc's (Airy's disc) surrounded by alternate dark and bright Airy rings.
- Consider that, the lens is very close to circular aperture or the screen is at a far distance from the lens,
- Therefore, $\sin\theta = \theta = \frac{r}{f}$, -------------(1)
- Where, f =Focal length of lens.
- We have 1st secondary minima condition only when,

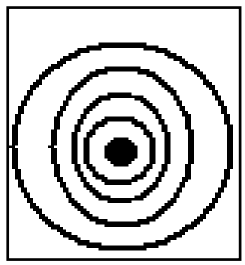
$$d\sin\theta = 1\times\lambda \quad \text{or} \quad \sin\theta = \theta = \frac{\lambda}{d} \text{ -----------(2)}$$

From (1) and (2)

$$\frac{r}{f} = \frac{\lambda}{d}$$

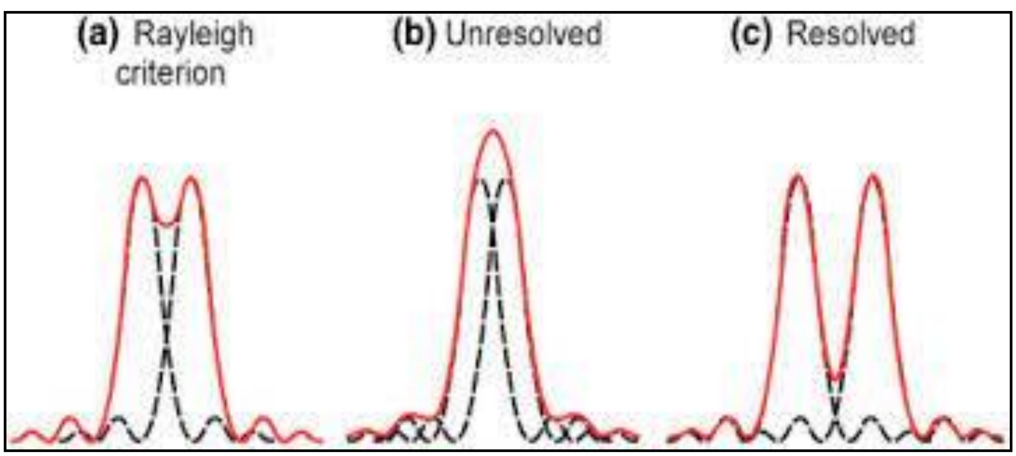
$$r = f \times \frac{\lambda}{d}$$

- Where r is radius of Airy's disc, so as the diameter of aperture decreases the radius of Airy's disc increases.
- The diffraction pattern consisting of a central bright disc surrounded by bright & dark rings. The central bright disc is often called Airy's disc.



5. Rayleigh's criterion for resolution

- The Rayleigh criterion states that two closely spaced point sources are just resolved by an optical instrument only if central maximum in the diffraction pattern of one coincide the first minimum in the diffraction pattern of the other and vice-versa.



- Two-point sources are regarded as just resolved when the principal diffraction maximum of one image coincides with the first minimum of the other. Shown in above (figure a).
- If wavelengths of the two sources are small, then their principal maxima will be still nearer said to be unresolved shown in above (figure b).
- The principal maxima of two wavelengths are largely separated. Hence two wavelengths are said to well resolved shown in fig (c).

6. Resolving Power

- The ability of the instrument to produce just separate diffraction pattern of two close objects is known as its resolving power.

Resolving Power of Telescope

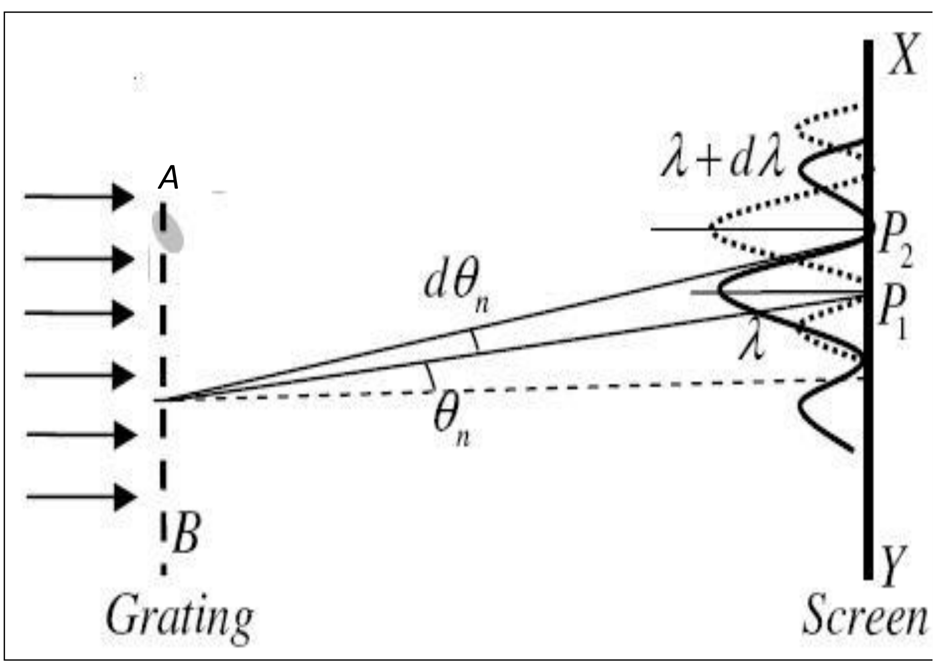
- In telescopes, very close objects such as binary stars or individual stars of galaxies subtend very small angles on the telescope.
- To resolve them we need very large apertures. We can use Rayleigh's to determine the resolving power. The angular separation between two objects must be

$$\Delta\theta = 1.22\frac{\lambda}{d}$$

$$\text{Resolving power } = \frac{1}{\Delta\theta} = \frac{d}{1.22\lambda}$$

- Thus higher the diameter *d*, better the resolution. The best astronomical optical telescopes have mirror diameters as large as 10m to achieve the best resolution.
- Also, larger wavelengths reduce the resolving power and consequently radio and microwave telescopes need larger mirrors.

Resolving Power of grating



- Let *AB* represent the surface of a plane transmission grating having a grating element *(a+b)* and *N* total number of slits.
- Let a beam of light having two wavelengths λ and dλ is normally incident on the grating.
- Let P_1 is *nth* primary maximum of a spectral line of wavelength λ at an angle of diffraction ϴ and P_2 is the *nth* primary maximum of wavelength $(\lambda + d\lambda)$ at a diffracting angle $\theta_n + d\theta_n$

- According to Rayleigh criterion, the two wavelengths will be resolved if the principal maximum $(\lambda + d\lambda)$ of *nth* order in a direction $\theta_n + d\theta_n$ falls over the first minimum of *nth* order in the same direction $\theta_n + d\theta_n$
- Let us consider the first minimum of *nth* order in the direction $\theta_n + d\theta_n$ as below.
- The principal maximum of λ in the ϴ direction is given by

  $(\boldsymbol{a} + \boldsymbol{b})\boldsymbol{sin\theta_n} = \boldsymbol{m\lambda}$............... (1)
- The principal maximum of (λ+dλ) in the $(\theta_n + d\theta_n)$ direction is given by

  (a+b)sin $(\theta_n + d\theta_n)$=m (λ+dλ) ------ (2)
- The equation of minima is $N(a + b)sin\theta_n = m\lambda$

  Therefore, $(a + b)sin\boldsymbol{\theta_n} = \frac{\lambda}{N}$ ------ (3) Where, m= 1
- The two wavelengths are said to be just resolved only when Principal maxima of angle of diffraction $(\theta_n + d\theta_n)$ falls over minima of wavelength λ by addition of path difference $(\frac{\lambda}{N})$ in equation (1).
- Therefore,

$$(\boldsymbol{a} + \boldsymbol{b})\boldsymbol{sin}(\theta_n + d\theta_n) = \boldsymbol{m\lambda} + \frac{\lambda}{N}) \text{ --------------(4)}$$

Compare equation (2) and (4) we get,

$$m(\lambda + d\lambda) = \boldsymbol{m\lambda} + \frac{\lambda}{N})$$

$$\therefore \quad m\lambda + md\lambda = m\lambda + \frac{\lambda}{N})$$

$$\therefore \quad md\lambda = \frac{\lambda}{N}$$

Resolving Power = $= \frac{\lambda}{d\lambda} = mN$,

Steps and formula

Problem based on

Diffraction of Light

- **Single slit diffraction:**
  - condition of principal maxima:
    $\theta = 0$.
  - condition of minima:
    $a\sin\theta = \pm n\lambda$, **n=1, 2, 3 ....**
  - condition of secondary maxima:
    $a\sin\theta = \pm(2n+1)\frac{\lambda}{2}$, **n=1, 2, 3 ....**
  - Total angular width of central maximum:
    $2\theta = 2\sin^{-1}\frac{\lambda}{\alpha}$

Diffraction grating:

- Conditions of principal maxima are

  $(a+b)\sin\theta = \pm m\lambda$, **m=0,1, 2, 3 ....**

- Conditions of minima are

  $N(a+b)\sin\theta = \pm m\lambda$, **(m may have all valued except 0, N, 2N, 3N..)**

- **Resolving power of grating:**
  - R.P of grating $= \frac{\lambda}{d\lambda} = mN$,

EXERCISE-1.2
Problem based on Diffraction

Q.1 What do you mean by diffraction?

Q.2. Derive an expression for resultant amplitude and resultant intensity between diffracted waves in fraunhofer diffraction due to single slit.

Q.3 Write the conditions of maxima and minima in diffraction patterndue to single slit?

Q.5 Find half angular width of central maximum in Fraunhofer diffraction Pattern of a slit of width 12×10^{-5}cm, when illuminated by light of wavelength $6000A^{\circ}$.

Q.6.A monochromatic light of wavelength 5500 A^0 incident normally on slit of width 2×10^{-4}cm Calculate angular position of first and second minimum.

Q.7. What is highest order spectrum that is visible with light of wavelength $6000A^{\circ}$ by means of grating having 5000 lines per cm?

Q.8. How many liner per cm are there on surface of plane transmission grating which gives 1^{st}order light of wavelength $6000A^{\circ}$ at an angle of diffraction 30°.

Q.9. A grating has 620 rulings/mm and is 5.05 mm wide. What is the smallest wavelength interval that can be resolved in third order at $\lambda = 481mm$?

Q.10. A Plane grating just resolve two lines in the second order. Calculate grating element if $d\lambda = 6A^{\circ}$, $\lambda = 6\times10^{-5}$cm & width of ruled surface is 2 cm.

Q.11. Calculate minimum numbers of lines in a grating which will just resolve in 1^{st} order whose wavelengths are $5890A^{\circ}$ & $5896A^{\circ}$.

MILESTONE-3

13. Introduction to Polarization
14. Brewster's Law
15. Malus law
16. Double refracting Crystal
17. Huygen's theory of double refraction.
18. Applications of polarization- LCD

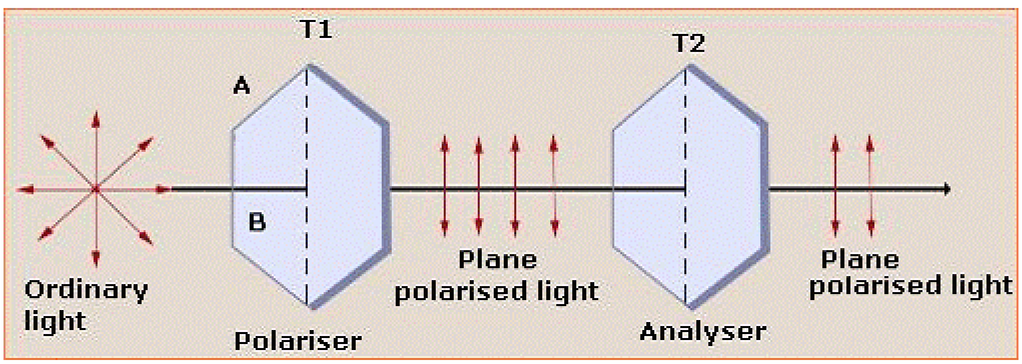
13. Introduction to Polarization

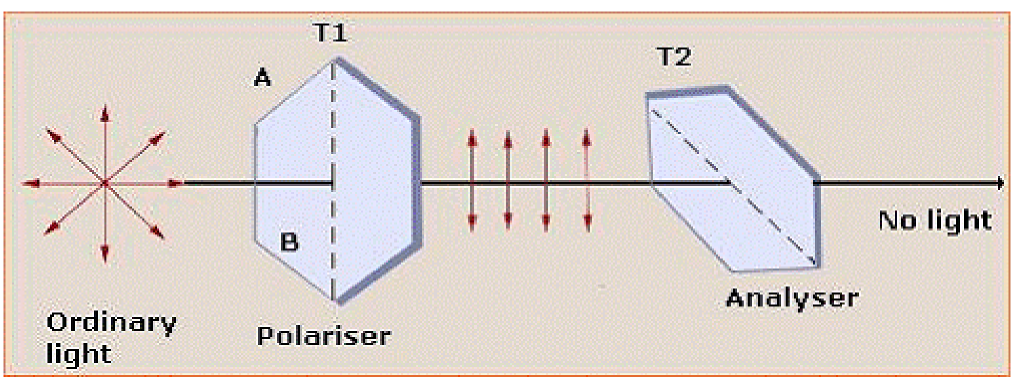
- Polarization, in Physics, is defined as a phenomenon caused due to the wave nature of electromagnetic radiation.
- Sunlight travels through the vacuum to reach the Earth, which is an example of an electromagnetic wave.
- These waves are called electromagnetic waves because they form when an electric field interacts with a magnetic field.
- The interference and diffraction phenomenon establishes the wave natureof light but fail to check the exact nature of light waves.
- The exact nature of light waves that are transverse nature has been established by the polarization phenomenon.
- Rasmus Bartholin (Erasmus Bartholinus) was the first to report on a physical effect based on what we call today "polarization", where he presents the astonishing properties of calcite crystal.
- There are two types of waves longitudinal or transverse wave.
- In the longitudinal wave vibration of particles is parallel to the propagation of waves and in the transverse wave vibration of particles is perpendicular to the propagation ofwaves.
- In a transverse wave, particles execute periodic vibration in many numbers of directions. So, two similar transverse waves may differ from one another due to their different direction of vibration.
- Therefore, transverse waves in which vibrations are restricted to the direction of one particle cannot be symmetrical and must exhibit some characteristics having any relation to the direction of propagation.
- This dependence of certain properties on directions or this property of asymmetry or one-sidedness is calledpolarity.

- A wave having such a characteristicis said to be polarized and the phenomenon is called polarization.
- The phenomenon in which light restrict to vibrate in a single direction is called polarization.
- The polarization of light affects the focus of laser beams, influences the cutoff wavelengths of filters, and can be important to prevent unwanted back reflections.
- It is essential for many metrology applications such as stress analysis in glass or plastic, pharmaceutical ingredient analysis, and biological microscopy.
- Different polarizations of light can also be absorbed to different degrees by materials, an essential property for LCD screens, 3D movies, and your glare-reducing sunglasses.

Polarization of Light

- This is an optical experiment used to demonstrate transverse characteristics of lightwaves.
- In this experiment, ordinary light incident normally on a crystal plate (T_1) i.e. on a thin plate of tourmaline of calcite crystal, cut with faces parallel to its vertical axis.





- When T_1 and T_2 are parallel to each other or rotate simultaneously, the intensity of transmitting light remains the same.
- But if plate T_1 is kept fixed and only T_2 is rotated then the intensity of transmitting light decreases and become zero when $T_1$and T_2 are exactly perpendiculars to each other.

- And again, goes on increasing if rotated that crystal T_2 and total light transmitted when T_1andT_2 become exactly parallel to each other.
- This shows the transverse nature of light.

Some important Concept

Unpolarised Light

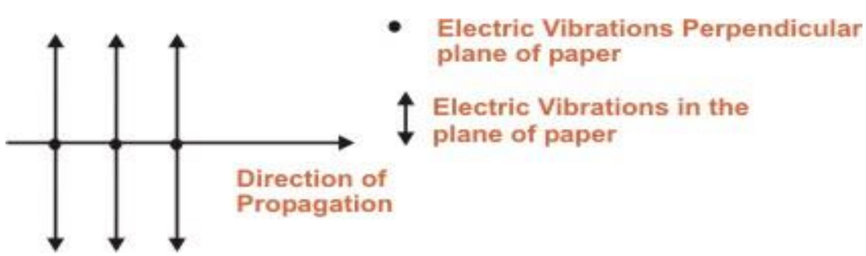
- The ordinary light beam having vibrations along all possible plane perpendicular to the direction of propagation is said to be unpolarized light.Figure(b)

Polarised Light

- The light beam having vibrations along the single direction perpendicular to the direction of propagation of light is called plane polarizedlight.Figure(a)

(a) Polarized light (b) Unpolarized light

- When plane polarized light has vibrations in plane of paper they are denoted by a straight arrow and when vibration present in perpendicular to plane of paper represented by dots.



Difference between Polarized and Unpolarised light

Polarized Light	Unpolarized Light
The oscillation is confined to only one plane.	The oscillation occurs in many planes.
It is absolutely coherent in nature.	It is incoherent in nature
Its intensity depends on the nature of polaroid used.	Its intensity depends on the nature of source.
In polarized light electric vector is confined	In unpolarized light plane of vibration of

to a plane and magnetic vector H is normal to the plane.	electric vector continuously and C random change.

Plane of Polarization

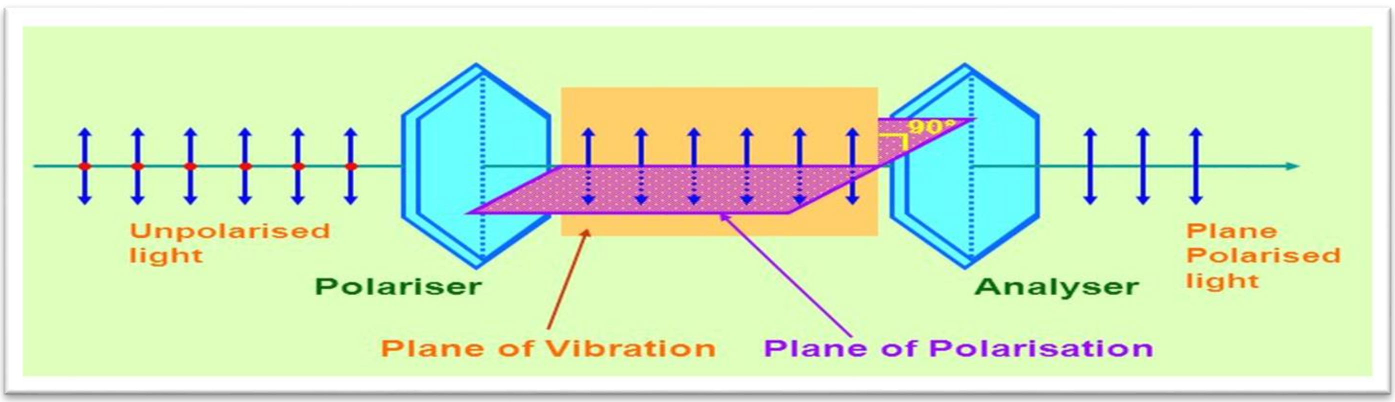
- The plane containing the direction of propagation of light, but containing no vibrations is known as the plane of polarization.

Or

- The plane perpendicular to the plane of vibration is known as the plane of polarization.

Plane of Vibration

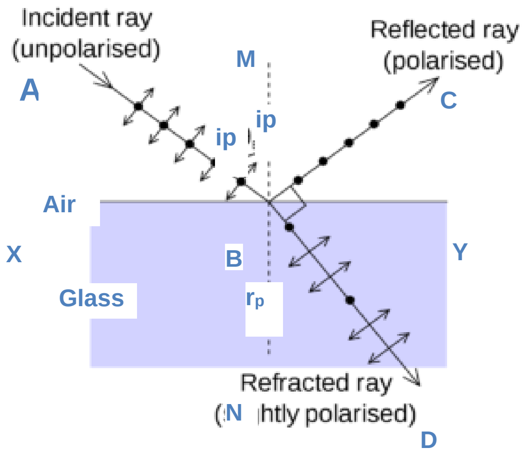
- The plane containing the crystallographic axis, the direction of vibration and direction of propagation of light is known as the plane of vibration.
- The plane of polarization is always perpendicular to the plane ofvibration.



Figure(d)

14. Brewster's Law

- When unpolarized light of certain wavelength is incident upon the surface of a transparent substance it experiences maximum plane polarization at the angle of incidence whose tangent is the refractive index of the substance.



- Above figure (e) shows a beam of AB of unpolarized light incident upon a surface XY of a glass slab at the polarizing angle i_p.
- The reflected beam BC is completely plane polarized and the refracted beam BD is partially plane polarized.
- Let r_p is the angle of refraction.
- According to Brewster's Law,

Angle $CBD = 90^\circ$

But from above diagram, We have

$$ip + rp = 90^\circ$$

Therefore, $rp = 90^\circ - ip$

$$\mu = \frac{\sin i_p}{\sin r_p} = \frac{\sin i_p}{\sin(90 - ip)} = \frac{\sin i_p}{\cos r_p}$$

But

$$\text{or } \mu = \tan i_p$$

15. Malus Law

- When unpolarised light is incident on the polarizer, then transmitted light is plane polarized.
- Then plane polarized light is incident on the analyzer and get transmitted.
- The intensity of light transmitted by the analyzer varies with the angle between the plane of the polarizer andanalyzer.
- Consider two tourmaline plates i.e. polarizer and analyzer are arranged in a parallelway.

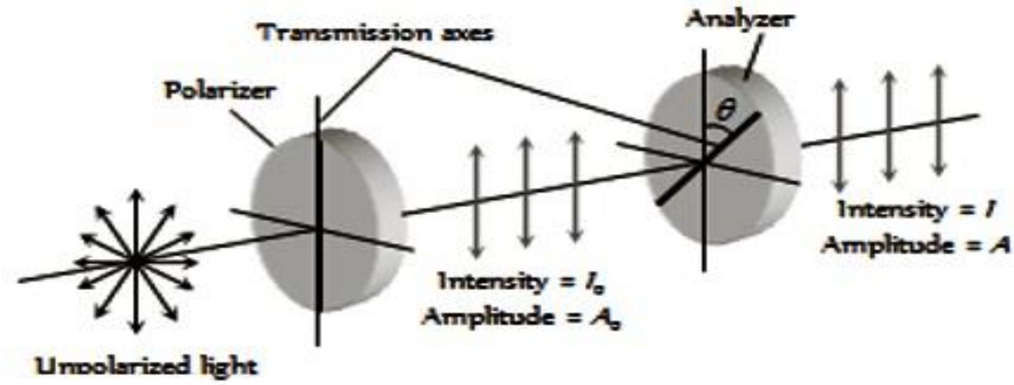


Figure (f)

- A beam of unpolarized light incident normally on polarizer.
- Then transmitted light incident on the analyzer and again get transmitted.
- If polarizer is kept fixed and analyzer is rotated about the direction of propagation, intensity of light transmitted by analyzer get changes.
- The law of malus states that, when a completely plane polarized light beam is incident on the analyzer, then the intensity of polarized light emerging from analyzer is proportional to the square of cosine of the angle between planes of polarizer and analyzer.
- Therefore, according to the law ofmalus,

$$I \alpha \cos^2 \theta$$

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

I = Intensity of light transmitted by the analyzer.

I_0= Intensity of light transmitted by the polarizer.

θ = angle between the plane of the polarizer and the plane ofthe analyzer.

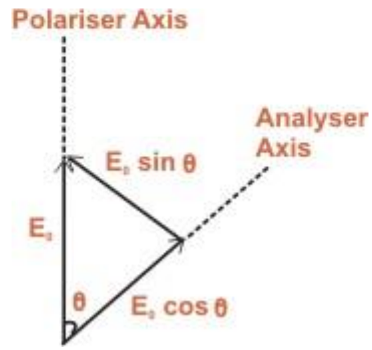
- If E_0= amplitude of plane polarized light incident on the analyzer. It can resolve into two Component.

i) $E_0 \cos\theta =$ Parallel to the plane of the analyzer.

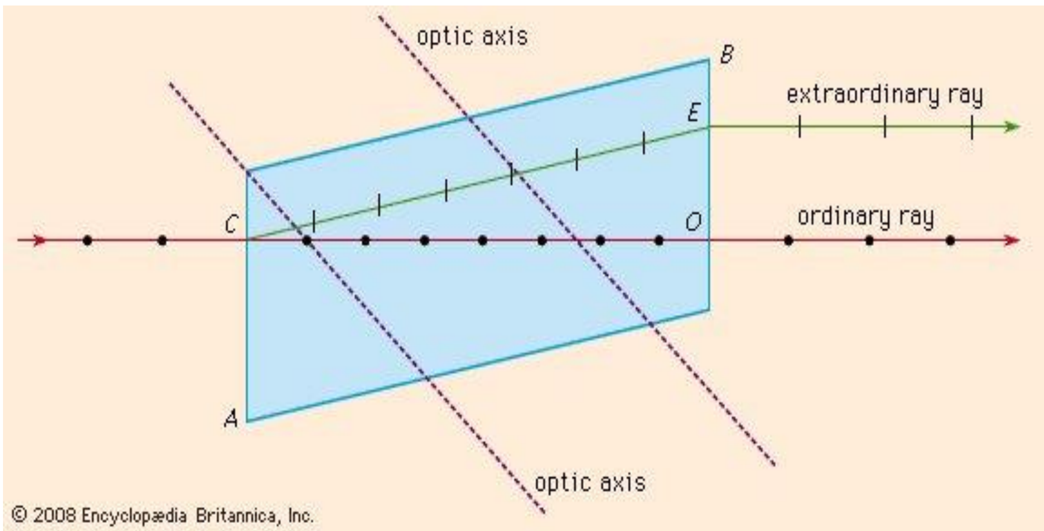
ii) $E_0\ sin\theta$ = Perpendicular to the plane of the analyzer.

- Out of these two, the only parallel component $E_0 \cos\theta$ is transmitted and perpendicular component $E_0\ sin\theta\ \ is$ cut-off.

$$I = (\text{Amplitude})^2 = (E_0 \cos\theta)^2 = E_0^2 \cos^2\theta = I_0 \cos^2\theta$$



16. Doubly Refracting Crystals



- When a beam of ordinary light is allowed to pass through calcite or quartz crystal,then we get two refracted beams.
- But in case of glass, we get only one refracted beam. This phenomenon is called double refraction or birefringence.
- Certain crystal which shows this property of splitting of the light ray is called as double refracting crystal.
- **Uniaxial crystals**: In uniaxial crystals, there is only a single direction called as optic axis along which two refracted rays are transmitted with the same velocity. Out of these two refracted rays, only one follows the ordinary laws of refraction.

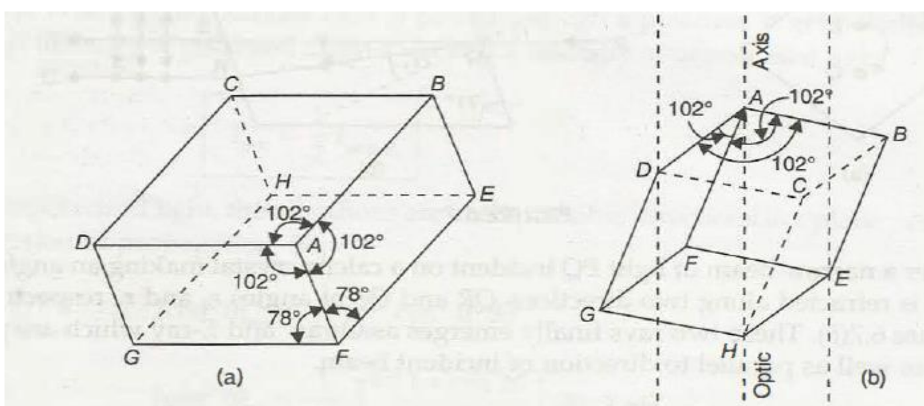
  Examples: Tourmaline, Calcite and Quartz**.**
- **Biaxial crystals:** In biaxial crystals, there are two directions or two optic axes along which the velocities of refracted rays are the same. None of the refracted rays obeys the laws of refraction**.** Examples: Topaz,Argonite,Copper sulphate,cane sugar and mica.
- **Calcite crystals:** calcite is colorless and transparent crystal. It is also called Iceland spar because found in large quantities in Iceland.Naturally occurring calcite crystals shown in figure(g) has rhombohedral cleavage.

Figure (g)

- It is bounded by six faces shown in the figure (h), each of which is a parallelogram with angles equal to 102° and 78°.
- The rhombohedron has only two corners A and H where all the face angles are obtuse (102°), these two corners appear at the blunt corners of the crystal.
- At the rest six corners one angle is obtuse (102°) and two are acute (78°).

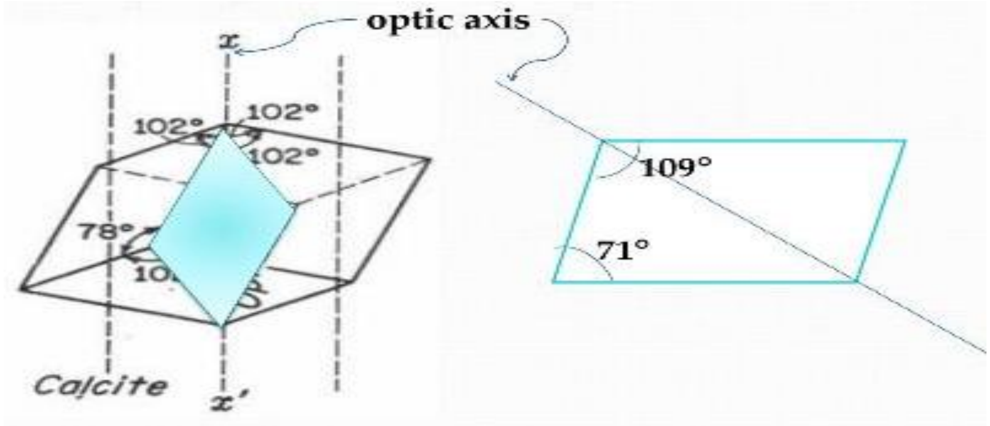
Optical Axis of Doubly Refracting Crystal

- The optic axis of doubly refracting crystal is a direction along which all plane waves are transmitted with a single velocity without showing the effect of double refraction.
- Or a line bisecting any one of the blunts corners (A, or H)and making equal angles with each of three edges meeting there, is an optic axis. (Figureh)
- Any line parallel to this line is also an optic axis.



Principal Plane or Principal Section of Doubly Refracting Crystal

- A plane containing the optic axis of the crystal and perpendicular to its two opposite refracting faces are known as a principal section or principal plane of crystal for that pair of faces shown in the figure

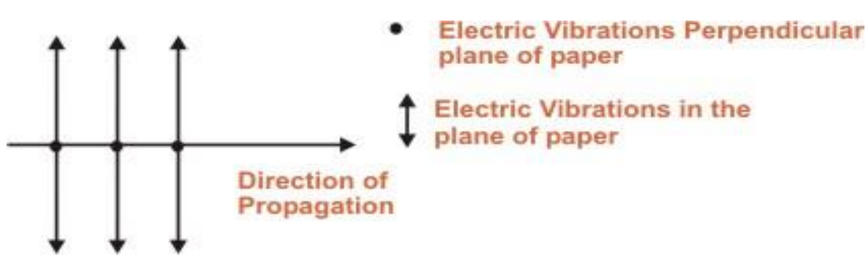


- (a) (b)

- Thus, there are three principal sections of the crystal for that pair of the face.
- A principal section always cuts the surface of calcite in parallelogram having angles 109° and 71°.

Ordinary and Extra-ordinary Rays

- When a light ray incident on the double refracting crystal is split into tworays, .e. ordinary ray(O-ray) and extra-ordinary ray(E-ray)
- Out of these two rays, ordinary rays are plane polarized in principal plane, i.e. its vibrations are perpendicular to the principal plane and they are at right angles to plane of the paper shown bydots (.)
- While extra-ordinary rays are plane polarized in a plane parallel to principal plane i.e. its vibrations are in a principal plane. They are in the plane of the paper shown by arrow.

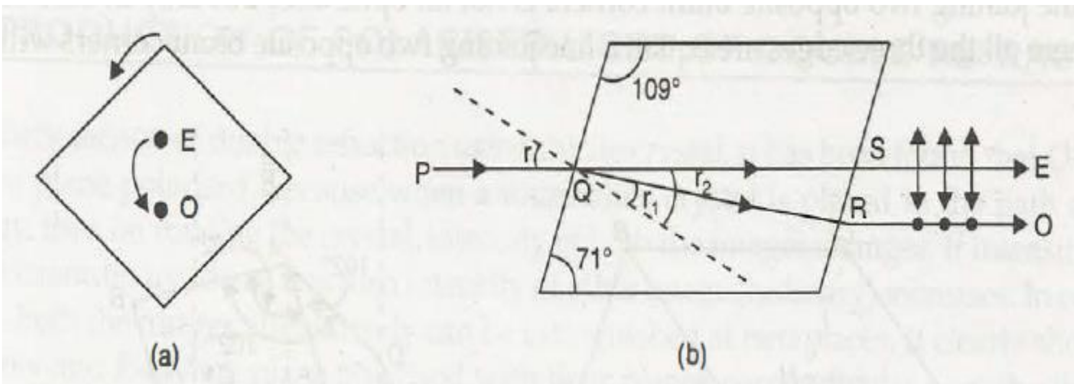


Special cases

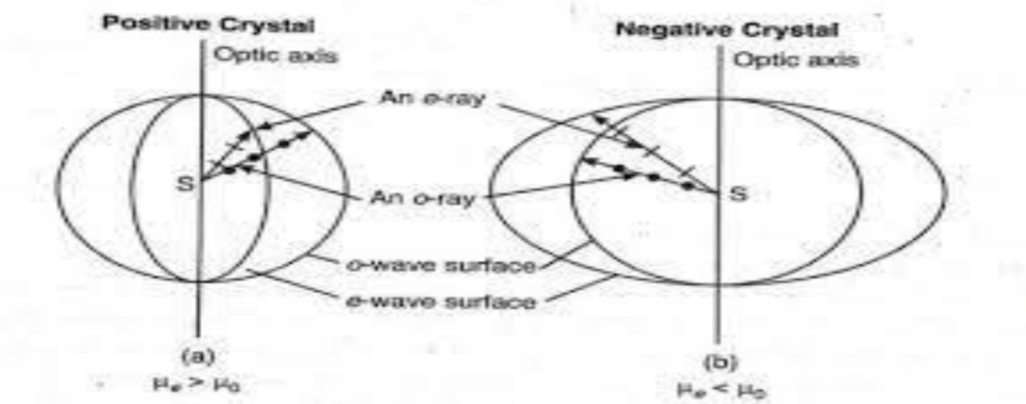
- If a beam of an unpolarised light incident along the optic axis or parallel to the optic axis, it is split up into O-ray and E-ray and both ray travel along the same direction with samevelocities.
- If a beam of unpolarised light incident normally to optic axis, then beams split up into O-ray and E-ray, but both ray travel along the same direction with different velocities.

17. Huygens's Theory of Double Refraction

- Huygens's explained the phenomenon of double refraction in uniaxial crystals on the basis of the wave theory of light.
- When a beam of unpolarized light (PQ) incident on double refracting crystal, It splits into two refracted rays QS and QR i.e. E-ray and O-ray respectively figure.



- The ordinary wave travels with the same velocity (V_o) in all directions and so the corresponding wave front is spherical and R.I. of this wave is $\mu_0 = \frac{c}{v_0}$ and is constant.
- The velocity of extra-ordinary wave (V_e) varies with direction and hence corresponding wave front is elliptical and R.I. of this wave is $\mu_e = \frac{c}{v_e}$ and is different in different directions.
- The speed of both rays, i.e. E-ray and O-ray are same along the optic axis. Hence sphere and ellipsoid touch each other at a point on the opticaxis.
- In certain crystals such as calcite, tourmaline, etc,$V_e > V_o$,therefore ellipsoid is outside the sphere and so $\mu e < \mu o$.Such crystals are called as negativecrystals.
- In certain crystals such as quartz, ice etc, $V_o > V_e$, therefore sphere is outside the ellipsoid and so $\mu_0 < \mu_e$. Such crystals are called as positive crystals.



Optical activity

- When the plane polarized light is passed through a certain substance like sugar crystal, sugar solutions, quartz etc. plane of vibration is rotated.
- This phenomenon of rotation of the plane of vibration of plane polarized light is called

optical activity.

- The amount of rotation by which plane of vibration turned depends upon the thickness of

quartz plate and wavelength of the incident light.

- The substance which shows this property is called optically active substance.
- There are two types of optically active substance- Right-handed or dextrorotatory and Left-handed or Laevorotatory.

Right handed or dextrorotatory:

- The substance which rotates the plane of vibration in clockwise direction w.r.t. observer

looking towards light travelling towards him is called dextrorotatory.

Left handed or Laevorotatory:

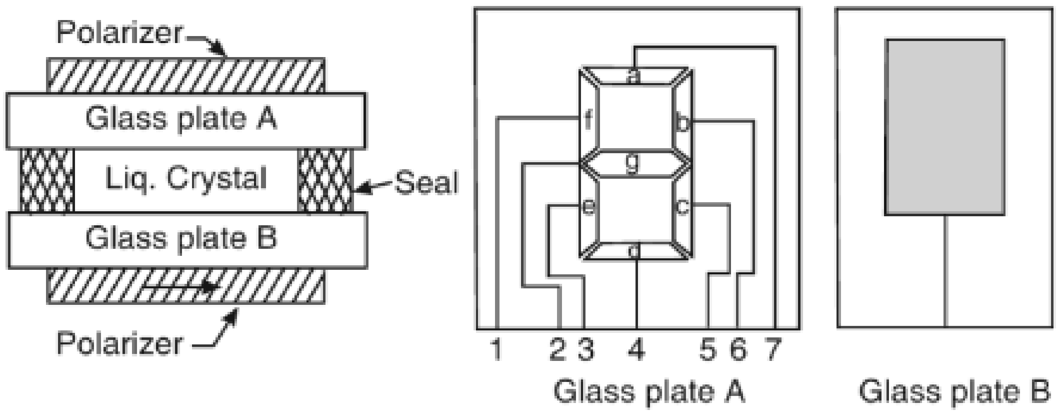
- The substance which rotates the plane of vibration in anticlockwise direction w.r.t. anobserver looking towards light travelling towards him is called levorotatory.
- Example. Cane sugar is dextrorotatory and fruit sugar is leavo rotatory and some quartz are dextro and some are leavo rotator depending on arrangement of molecules of quartz.

19. Applications of Polarization -Liquid Crystal Diode (LCD)

- Liquid Crystal Display is a passive device, i.e. does not emit light of its own, and works on the principle of polarization.
- The common applications of LCD are wrist watch, calculator, clock and general displays.
- In LCD liquid crystal is sandwiched between two glass plates. Out of these plates, glass plate A is etched in the form of seven segment display to display digits or alphabets.
- The whole assembly is placed between two polarizers with the crossed plane of

polarization.

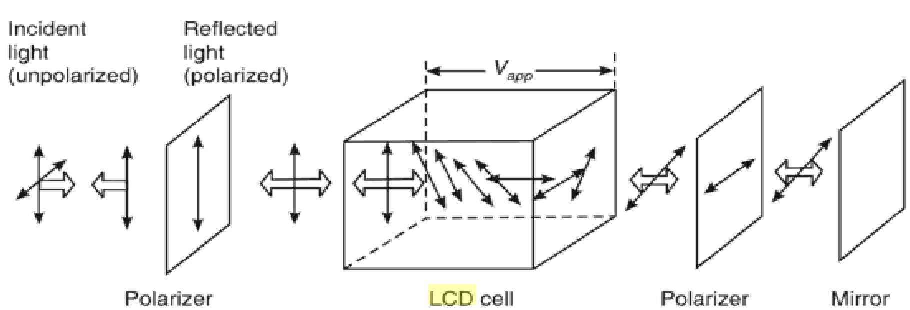
- Liquid crystals are optically active, which are able to rotate the plane of polarization of plane polarized light.
- Therefore, the thickness of the liquid crystal is taken in such a way that it rotates the plane of polarization by 90°.



(a) (b)

Working of LCD

- When an unpolarised light incident on polarizer1, it gets linearly polarized.
- After passing through the liquid crystal it gets rotated by 90° and therefore passes through the polarizer 2 whose transmission axis is perpendicular to that of polarizer1.
- The mirror on the back side reflects back the light which emerges unobstructed from front polarizer1.
- This produces uniform illumination.
- When an external voltage has applied the molecules within electrodes will get aligned in the direction of the field.
- Therefore, the plane of polarization will not change in this region and will be absorbed by the polarizer. This gives a dark digit or alphabets.



STEPS AND FORMULA

Problem based on

Polarization of light rays

Brewster's Law

$$\mu = \tan i_p$$

Law of Malus

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

EXERCISE1.3

Problem based on Polarization:

Q.1What is polarized and unpolarizedlight? Explain how the phenomenon of Polarization of light is used in liquid crystal display (LCD).

Q.2 State and explain Brewster's Law.

Q.3 What do you mean by polarization of light.

Q.4 State and explain Law of malus.

Q.5 Explain Huygens's theory of double refraction.

Q.6 A polarizer and analyzer are arranged so that amount of transmitted light is maximum. What will be percentage reduction in intensity of transmitted light when the analyzer is rotated through i) 30° ii) 90°

Q.7. Polarizer and analyzer are set with their polarizing directions parallel so that the intensity of transmitted light is maximum. Through what angle should either be turned so that the intensity be reduced to

(1) $\frac{1}{2}$ and (2) 25% of maximum intensity?

Q8. A polarizer & analyzer are arranged so that amount of transmitted light is maximum. What willbe percentage reduction in intensity of transmitted light when the analyzer is rotated through i) 30° ii) 90°

Q9. Polarizer and analyzer are set with their polarizing directions parallel so that the intensity of transmitted light is maximum. Through what angle should either be turned so that the intensity is reduced to?

(1) $\frac{1}{2}$ and (2) 25% of maximum intensity?

Q.10 A certain polarizer has a refractive index of 1.33. Find the polarization angle and angle ofrefraction?