Introduction

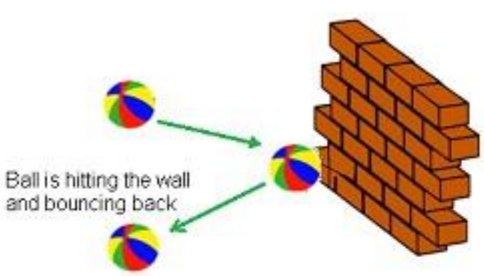
- This chapter explains the wave nature of light and all its properties which it exhibits due to its wave nature.
- Based on the wave nature how the laws of reflection of light and refraction of light can be proved.
- Some of the important applications of wave optics will also be discussed.
- For example: -
    - 3-D glasses which makes use of important property of wave optics i.e. how it uses the important property polarization.
    - Cameras used in taking photographs or camera recording for 3-D pictures.
    - Thin film used in the cars to protect from sunlight.

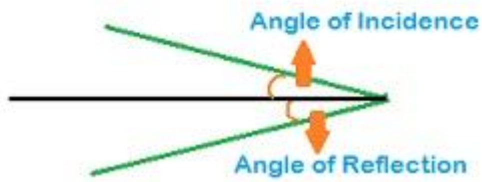

Light: A particle or a wave?

- Around 1800 and 1900, some of the scientists considered that light is a particle and according to some it was a wave.
- According to Newton's theory:-
    - Light is of particle nature. This means light is made up of small particles and those particles are known as <u>corpuscles</u>.
    - This theory was also known as corpuscular theory.
    - He proved the following phenomena by using the theory of mechanics :-

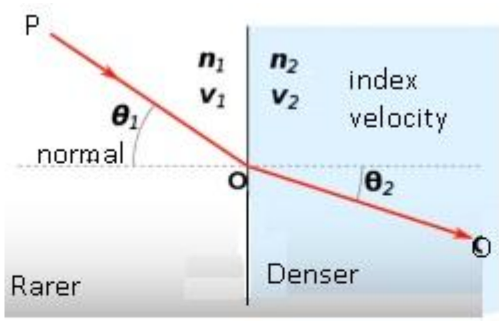
Reflection:-

- Consider the case of elastic collisions likein carom board.When we hit the striker, it strikes the boundary and bounces back.
- When the striker hits the boundary of carom board it is same as an incident ray. When it bounces back it is the reflected ray.
- Therefore in case of elastic collisions angle of incidence (i) is same as angle of reflection(r).
- He was able to prove that the phenomenon of reflection of light by considering light of particle nature.



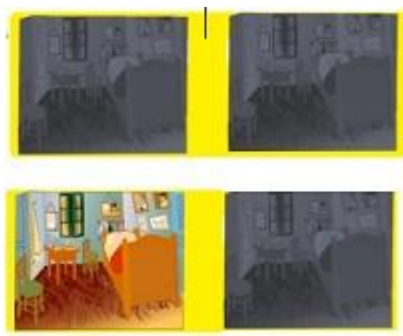


Refraction:-

- When light moves from a rarer medium to the denser medium it will bend towards the normal and when it moves from denser to rarer it bends away from the normal.
- According to Newton when the corpuscles strike the boundary, the particles of the denser medium tend to attract corpuscles.
- When the particles are deep inside the medium they will be attracted by all the other particles present in the medium.
- The net force on the corpuscles is when they are fully inside the denser medium.
- According to Newton's first law of motion, if the net force is 0, then the particle will continue to move in a straight line.
- Therefore as the net force on the corpuscles entering the denser medium is 0, they keep moving along a straight path.
- As there are attractive forces in one direction the corpuscles get accelerated. As a result there is increase in velocity. The particles slightly bend towards the normal.
- 

Rectilinear motion of light:-

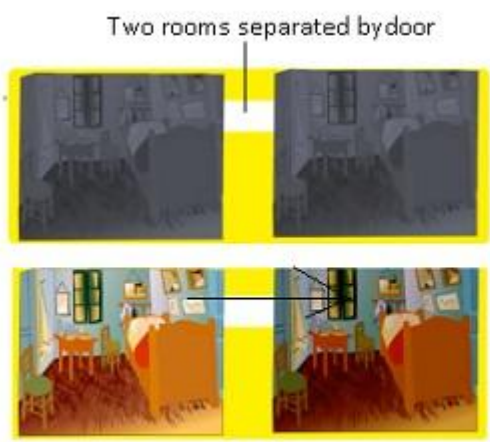
- Newton assumed there are 2 rooms side by side and are separated by a wall.
- If the window of first room opens, the light will enter the room.
- Light won't enter the second room as both the rooms are separated by a wall.
- According to him as light travels in straight line and whenever there is obstruction in between the light won't pass through the wall.
- This shows that light always travels in straight line.

- 
- The particle theory was accepted according to which light is made up of huge number of small - small particles known as corpuscles.

- <u>Shortcomings of corpuscular theory</u>
- This theory could not explain the phenomenon of refraction properly.
- When the corpuscles enter from rarer medium to denser medium,they get accelerated i.e. their velocity increases.
- This shows the velocity of the light particles in the denser medium is greater than the velocity of the light particles in the rarer medium.
- This means velocity of light in denser medium is more than rarer medium.
- Newton was not able to explain why the velocity of light is more in denser than in rarer medium.

Huygens Theory

- According to Huygens light can be of wave nature.



When switch is on in one room light enters the second room through door

- He got this idea from the simple observation:

- In an experiment conducted by Newton and Huygens, two rooms were considered with an obstruction in the middle. Newton considered a boundary and Huygens considered a door as the obstacle between rooms. In this experiment, light was switched on in one room.
- According to Newton if light travels in straight lines then first room will be bright and some portions of the second room will become bright and the rest of the room will be dark.
- Huygens observed that the first room became bright and the light spread in the second room as well, but it was not as bright as the first room.
- Therefore Huygens's proposed that light might be of a wave nature.
- As the wavelength of light is so small thereforethe wave nature of light cannot be seen.
- If the light is made to pass through a small portion which is comparable to the wavelength of light,then the wave nature of the light can be observed.
- According to Huygens, Newton's theory was not fully correct.Therefore he gave an idea that the light is of wave nature.
- For example:-
    - If a light is made to pass through a big window then the light will appear as ray and not the wave.
    - But if the light is made to pass through a very small hole then the wave nature can be observed.

Huygens's idea was not accepted because of the following reasons:-

- As there was no experimental proof of what Huygens proposed.
- There was Newton's authority at that time.
- Wave always needs a medium for propagation. This means light cannot propagate in vacuum.But sunlight is able to reach earth surface.

Conclusion given by Huygens formed the basis of <u>wave nature of light</u>.

Many other scientists came after Huygens to prove light is of wave nature :-

Thomas Young (1800)– Young performed very important experiment known as Young's double-slit experiment. He was able to prove:

- The wave nature of light.

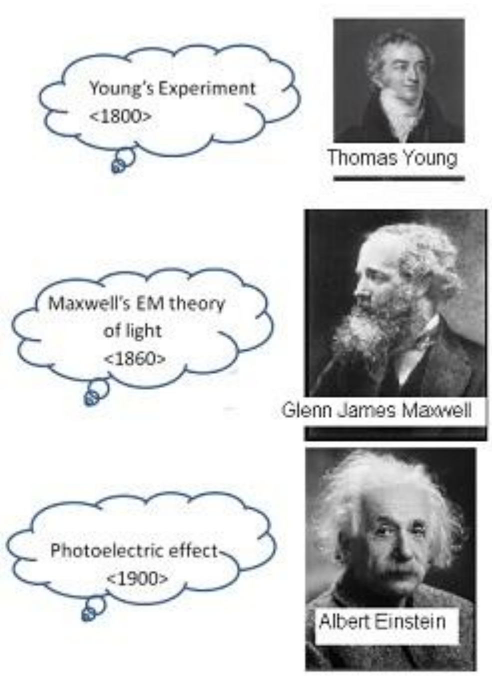
Maxwell(1860)- Maxwellgave the Maxwell's EM theory of light.

- He was able to provethere are visible light in the Electromagnetic spectrum.
- He supported the wave nature of light and he also predicted the speed of the light.

After Maxwell, the wave nature of light was accepted and Newton's corpuscular theory was proved wrong.

Around 1900 some of the scientists observed the photoelectric effect.

- In photoelectric effect when the light falls on the metal surface, electrons get ejected from the metal surface.
- Einstein explained the photoelectric effect by the particle nature of light.



<u>Light: A particle or a wave: Conclusion</u>

- Dual nature of light.
  - Light has both wave as well as particle nature.
  - Light can behave either as a particle and or a wave depending on the situations.
  - Dual nature is also shown by electrons.
- When particle nature of light is considered then the Photoelectric effect, ComptonEffect, etc. can be considered.
- When wave nature of light is considered then wave properties such as interference, diffraction, polarization, etc. are considered.

Characteristics of Waves

<u>Amplitude: -</u>

- Amplitude is the maximum displacement of the elements of the medium from their equilibrium positions as wave passes through them.
  - It is denoted by A.

Phase:-

- Phase of a wave describes the state of motion as the wave sweeps through an element at a particular position.

Wavelength:-

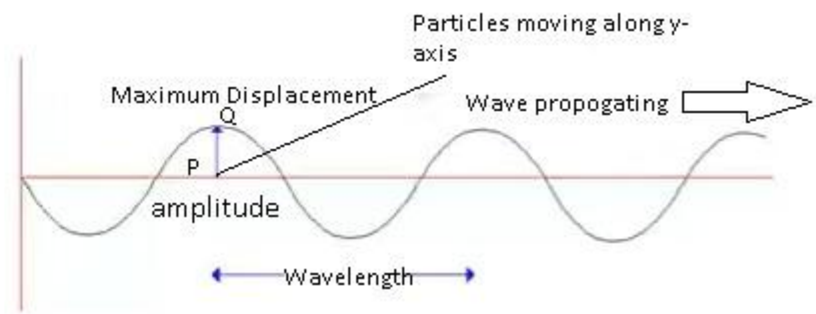
- Wavelength is defined as the minimum distance between two consecutive crests or two consecutive troughs when in the same phase.
    - It is denoted by λ.

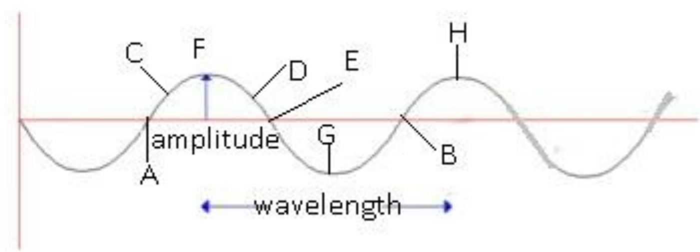
Time Period of a wave: -

- Time Period of a wave is the time taken through one complete oscillation. It is denoted by 'T'.

Frequency of a wave:-

- Frequency of a wave is defined as number of oscillations per unit time. It is denoted by ν.
- $\nu = 1/T$.

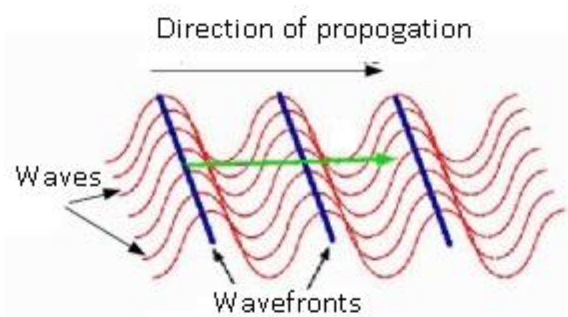


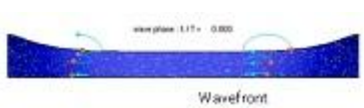


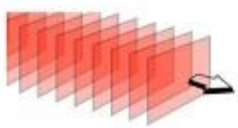
- Consider two points A and B on a wave. Their positions as well as their behaviour are same. Therefore points A and B are in phase.
- Consider the points F and G their positions are same but the behaviour is totally opposite. So F and G are out of phase.

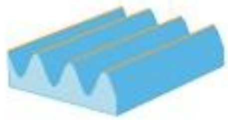
Wavefront

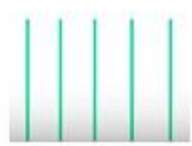
- Wave front is defined as locus of all points having same phase at a given instant of time.
- The shape of wavefront depends on the shape of the source of disturbance.
- A wavefront is always normal to the light rays.
- A wavefront does not propagate in the backward direction.











- There are 3 types of wavefronts:-
    - Spherical wavefront(spherical in shape)
    - Plane wavefront(linear in shape)
    - Cylindrical wavefront(cylinder in shape)

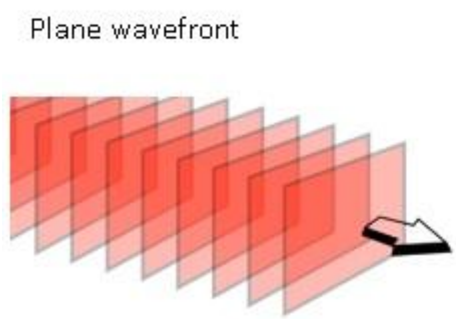
Spherical Wavefront

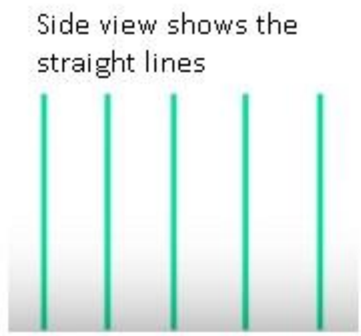
- When the source of light is a point source the wavefront formed will be spherical wavefront.
- Point source means the source of light is so small that it is considered as point. It can be considered as dimensionless.
- For example: - Ripples in water are in the form of concentric circles which are spherical wavefronts.



Plane Wavefront

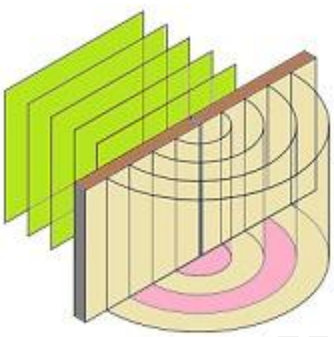
- When the small part of a spherical or cylindrical wavefront originates from a distant source like infinity then the wavefront which is obtained is known as plane wavefront.
- For example: -Rays coming from infinity like Sun.

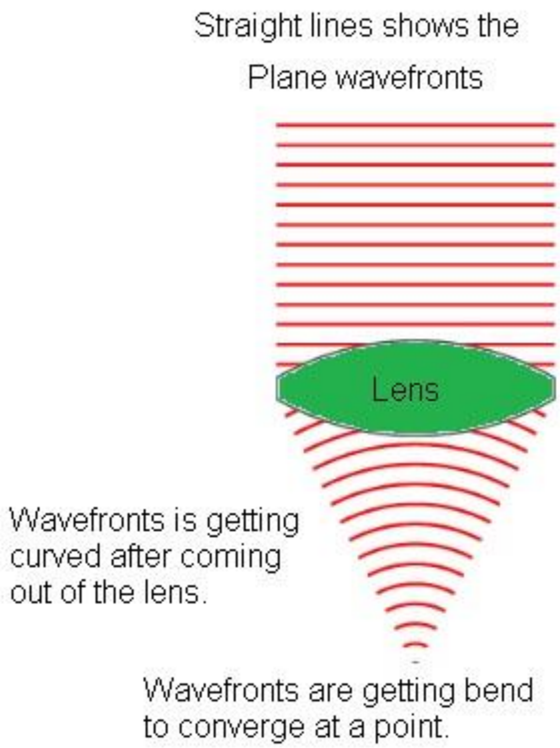




Cylindrical Wavefront

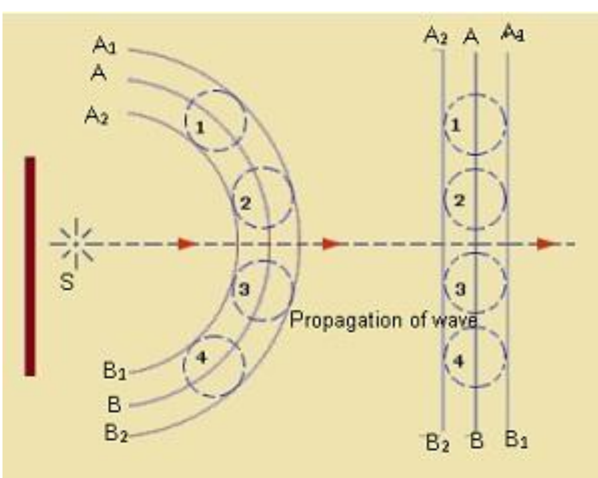
- When the source of disturbance is a slit (i.e. line source) then the wavefront is cylindrical because all the points are equidistant from the source and they lie on the surface of the cylinder.
- For example: - In the figure we can see when rays of lightfall on a lens after coming out of lens, they will converge at a point.
- The waves are bending and converging at a point so the shape of the wavefront is in the form of cylinder.
- Many concentric circles are formed and the wavefront is in the form of cylinder.

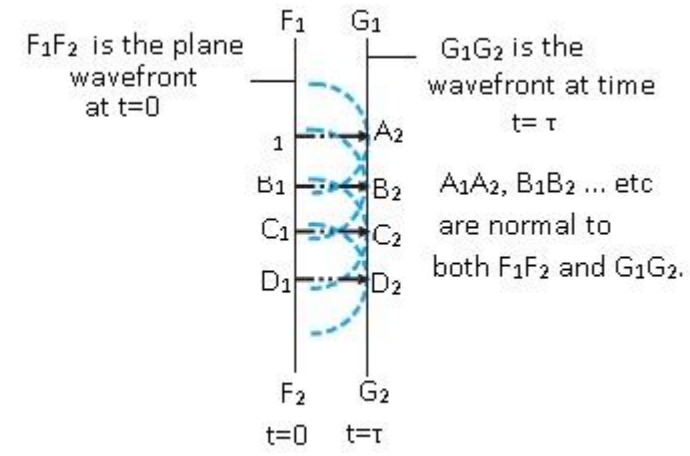




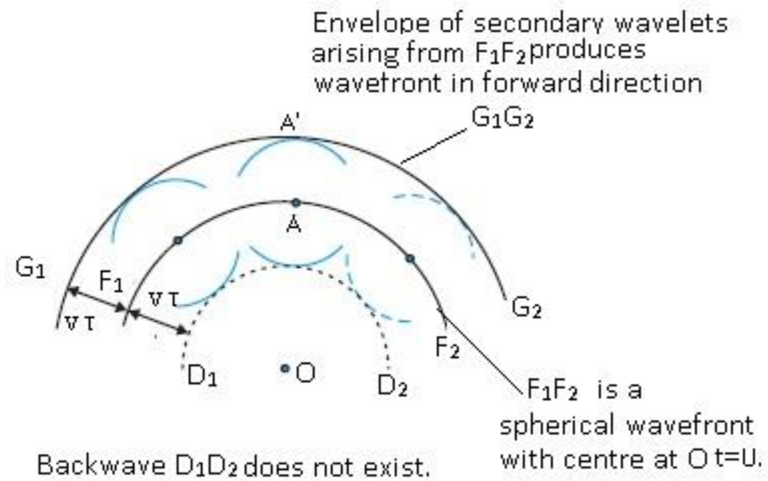
Huygens Principle

- Huygens principle states that each point of a wavefront is the source of secondary wavelets (small waves) which spread in all directions with the speed of the wave.
- The new wavefront is formed by drawing a line tangent to all the wavelets.



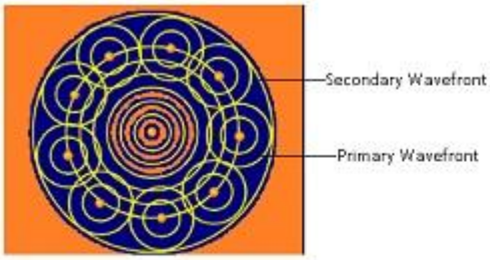


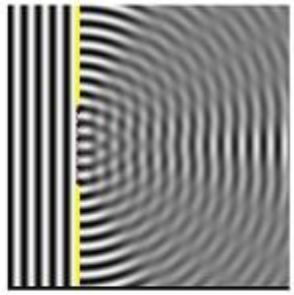
Geometrical representation of a plane wave

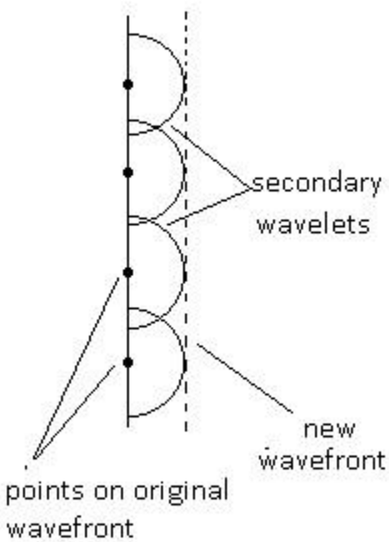


For example:-

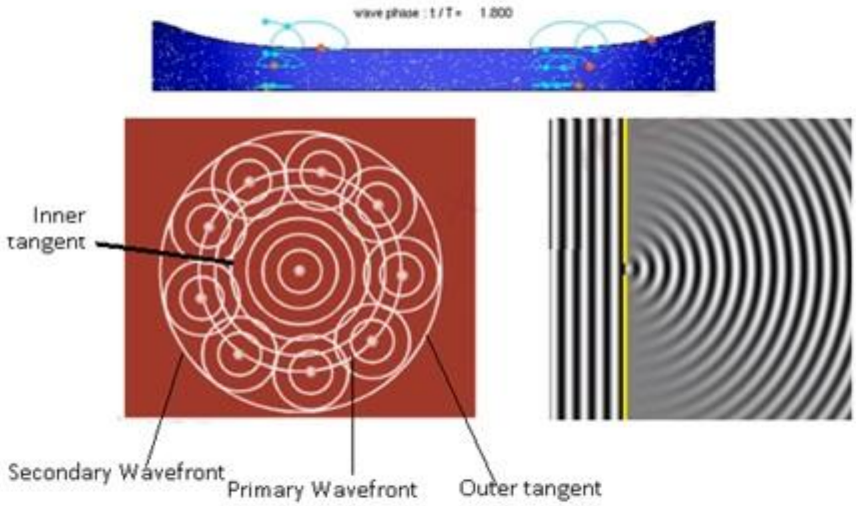
- If a stone is thrown in the river, waves will be formed surrounding that point.
- These waves look like concentric circles and they are known as wave fronts.
- The wave fronts gradually spread in all the directions.
- When the locus of all the waves is joined which are in the same phase, it will be the same as a sphere, and are known as Primary wavefront.
- Secondary wavefront are formed fromeach point on the Primary wavefront.
- The common tangential line that envelopes these secondary wavefronts will further give rise to other secondarywavefronts.
- All wavefronts will gradually fade after some time.
- **Conclusion**: - According to Huygens principle, every point on a wavefront give rise to secondary wavelets which spread out in all the directions with the speed of a wave.







- Using Huygens principle we can determine the new position of the wavefront after time t.
- Mathematically: To calculate the new position of the wavefront after time t.
- Let the initial time t_i =0.
- Each wave will travel $=vt_1$where v=speed of the wave.
- Distance travelled by each wave is equal to the radius of the sphere.
- Therefore radius of sphere = $v\ t_1$.
- Common tangent joining all the spheres will give the position of the new wavefront at time $t=t_1$.
- There are 2 possibilities: - outer tangent and inner tangent.
- The amplitude of the back wave is 0. Therefore the back wave is neglected and the forward wave was considered.
- New wave front will arise from each point on the outer wavefront.
- Therefore the distance covered by these wavefronts = vt_2.
- And again spheres will be obtained and by drawing common tangent will tell the position of all the new wavefront after time t_2.
- Again back wave is neglected and forward wavefront is considered.
- This shows the wavefront keep on spreading with time.



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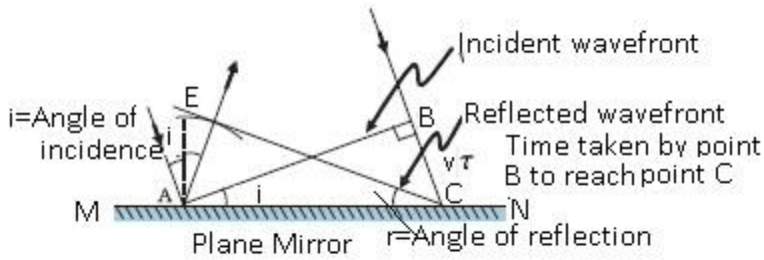
Reflection of plane waves

- When all the points on an incident wave which are in same phase are considered together, incident wave front will be obtained.
- After reflection incident waves will bounce back.
- Waves which are lighter will touch the surface before the waves which are denser.
- Let the time taken by some portion of wavefront to interact with the boundary is τ.
- As soon as incident wavefront touches the boundary, every point on the incident wavefront will give rise to secondary wavelets.
- The wavefront for the secondary wavelets will be a sphere.
- After some time t_1 incident ray is at some other point, again it will give rise to wavefront.
- Radius of the wavefront = velocity (speed) of the wave x time taken=vxτ.
- When other points interact with the boundary gradually, both τand radius will keep decreasing.
- As a result the tangent of all these points will give rise to reflected wavefront.
- Mathematically:-
    - Speed of the wave =v
    - Time taken by B to reach point C i.e. BC= vx τ
    - At point A it will give rise to secondary waves, therefore radius=vτ.
    - After some time τ will keep on decreasing.
    - Therefore as it moves towards the point C the radius of the sphere (wavefront) will keep on decreasing.
    - If a tangent is drawn then a reflected wavefront is obtained.



Refraction of plane waves

- In refraction, when any point of the incident wavefront interacts with boundary, secondary waves are generated and they will have some velocity.
- **Case 1**: Rarer medium to denser medium:-
- The waves generated in medium 1 will have velocity as $v_1\tau$.
- Waves in denser medium will have lesser velocity as compared to velocity in rarer medium.It is given as $v_2\tau$.
- The wavefront will not be a circle as the waves in two different mediums are travelling with different velocities.
- To prove Snell's law:-
    - Consider two triangle's ABC and AEC :-
    - In triangle ABC sin i= (BC/AC) and sin r=(AE/AC)
    - By dividing (sin i/sin r) = (BC/AC) x (AC/AE)
    - Therefore (sin i/sin r) = (BC/AE) =$(v_1\tau)$ /$(v_2\tau)$
    - => (sin i/sin r) =(v_1/v_2)
    - Refractive index n; =(c/V)
        - Where c = velocity of light in vacuum and V=velocity of light in medium.
- Therefore (sin i/sin r) = $(c/n_1)/(c/n_2)$
    - Where n_1 and n_2 are the refractive index in medium 1 and 2 resp.
- Snell's law (**sin i/sin r) = (n_1/ n_2).** Hence proved.
- Case 1: Angle of incidence is greater than angle of refraction, i>r
    - Light rays bend towards the normal when it travels from rarer medium to denser medium.
    - => $v_1 > v_2$
        - Where v_1 = velocity in denser medium and v_2 =velocity in rarer medium.

Case 2: Angle of incidence is less than angle of refraction, i<r.

Light rays bend away from the normal when it travels from denser medium to rarer medium.

=>$v_1 < v_2$

Conclusion: Velocity in rarer medium > Velocity in denser medium.

This is contrary to Newton's theory.

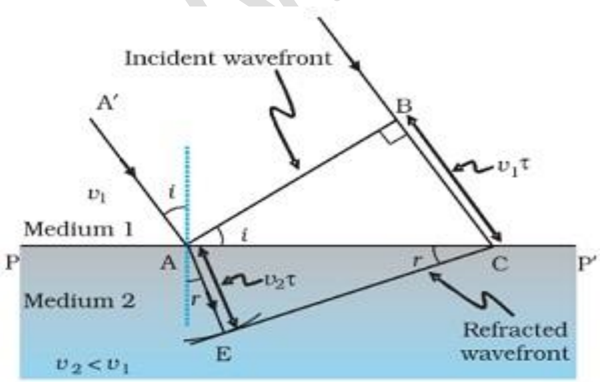
Huygens theory was able to prove all the laws of refraction. That is why his theory was accepted.

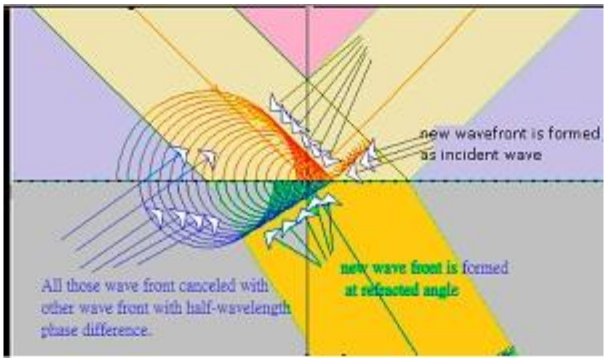
Case 2:- Denser medium to rarer medium.

- In refraction any point of the incident wave front interacts with boundary, secondary waves will be formed and these secondary waves will have some velocity.
- Velocity in denser medium is lesser than the velocity in the rarer medium, i.e.$v_1 < v_2$.
- => Radius of wave fronts in rarer medium < Radius of wave fronts in denser medium.

To prove Snell's law:-

- Consider two triangle's ABC and AEC :-
- In triangle ABC sin i= (BC/AC) and sin r=(AE/AC)
- By dividing (sin i/sin r) = (BC/AC) x (AC/AE)
- Therefore (sin i/sin r) = (BC/AE) =$(v_1\tau)$ /$(v_2\tau)$
- => (sin i/sin r) =τ.
- Refractive index n; =(c/V)
  - Where c = velocity of light in vacuum and V=velocity of light in medium.
- Therefore (sin i/sin r) = $(c/n_1)/(c/n_2)$
  - Where n_1 and n_2 are the refractive index in medium 1 and 2 resp.
- Snell's law (**sin i/sin r) = (n_1/ n_2).** Hence proved**.**
- Angle of incidence is less than angle of refraction, i<r.
- => $v_1 < v_2$.
- Special case: - If i = i_C => r = 90^0 . In this case there will be no refraction and total internal reflection takes place.
  - Where i_C= critical angle.

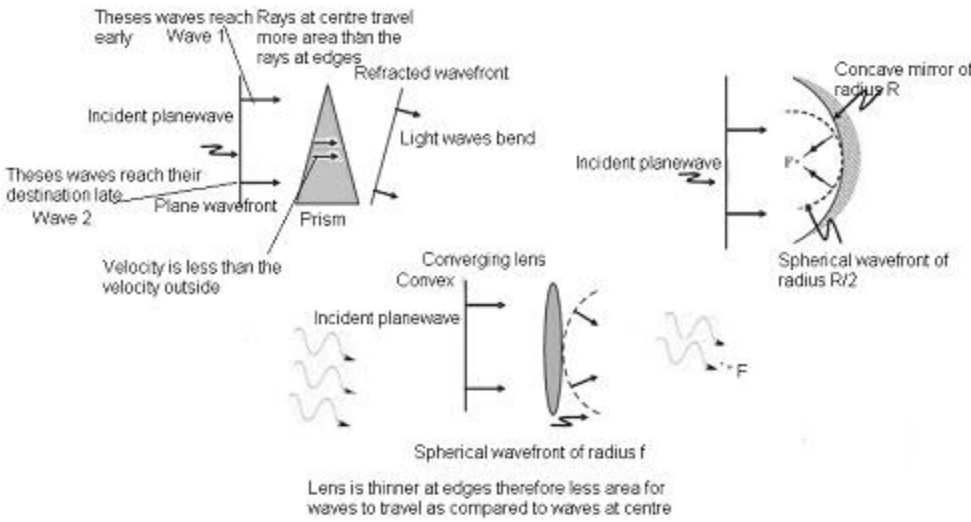




Examples for Refraction & reflection of plane waves

1. Prism:-
    1. Consider when the light waves are coming from a source which is at infinity.
    2. The wavefront will be plane wavefront.
    3. When these wavefront passes through prism, the light waves and also the wavefront.
    4. This shows the reflected wavefront.
2. Convex Lens(Converging Lens):-
    1. Consider the incident wavefrontpassing through a convex lens.
    2. The incident wavefront will converge at focus.
    3. As the light rays changes its direction, the wavefront will also change as a result a curved wavefront is obtained.
3. Concave mirror:-
    1. The concave mirror converges the incident wavefront at the focus which is at the same side.

- Effects ofPrism,convex lens and concave mirrorcan be explained in terms of wave front.
- According to Huygens velocity of the light in the denser medium is lesser than the velocity in the rarer medium.
    - In a prism or convex lens, velocity of wavefront inside them is lesser than the velocity outside.
    - Consider the fig the wave (1) will travel a very little portion of the denser medium whereas wave (2) will travel more portion of the rarer medium.
    - This means the velocity of wave (2) is less for longer period of time because of which they take more time to come out of the prism.
    - Wave (1) travel with lesser speed for small amount of time. So they reach faster.
- In case of convex lens the waves which are in middle will travel maximum portion of the denser medium. Therefore they travel more time in the denser medium.
- They have less velocity as a result they will take more time as compared to the waves at the edges.
- As the lens is thinner at both the edges.



Doppler's effect

- Doppler Effect is the shift in frequency of light when there is relative motion between the source and observer.
- It is used to measure the speed of a receding object.
- When the source is moving away from the observer then the wavefronts have to travel a greater distance to reach the observer.
- When a star is moving away from the earth the wavelength in the middle of the visible region of the spectrum moves towards the red end of the spectrum.
- As a result star looks more reddish when moves away from the earth.
- This is known as **red shift** phenomenon.
- When the waves are received from a sourcemoving towards the observer, there is an apparent decrease in wavelength. This is called **blue shift**.
- The fractional change in frequency $(\Delta v/v)=(-v_{radial}/c)$,
- Where v_{radial}= component of the source velocity along the line joining the
  - observer to the source; v_{radial} is considered positive when the source moves away from the observer.
- Thus, the Doppler shift can be expressed as:
- $(\Delta v/v) = (-v_{radial}/c)$;
- It is valid when the speed of the source is small compared to that of light.

Problem:-

What speed should a galaxy move with respectto us so that the sodium line at 589.0 nm is observedat 589.6 nm?

Answer:-

Since $\nu\lambda = c$,

$(\Delta \nu / \nu) = -(\Delta\lambda/\lambda)$ = (for small changes in ν and λ). For

$\Delta\lambda = 589.6 - 589.0 = +0.6$ nm

We get [using $(\Delta \nu/\nu) = -(v_{radial}/c)$

$(\Delta \nu/ \nu) = -(\Delta\lambda/\lambda) = -(v_{radial}/c)$]

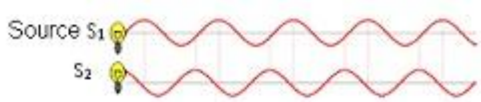
Or, $v_{radial} \cong +c(0.6/ 589.0) = +3.06 \times 10^5\ ms^{-1}$

= 306 km/s

Therefore, the galaxy is moving away from us.

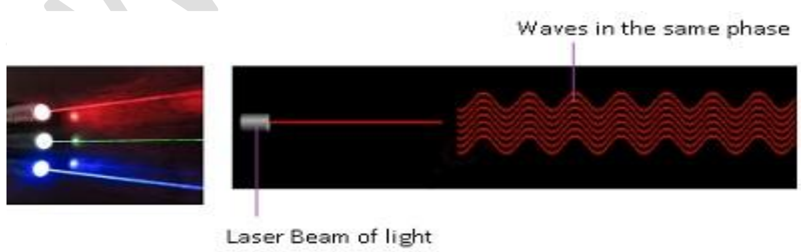
Coherent & Incoherent sources

- Coherent sources are those sources of light which emit waves that have same frequency and zero or constant phase difference.
- Suppose if there are 2 sources S_1 and S_2 are coherent sources if there frequencies are same and also phase difference between them is either 0 or constant.
- Phase difference should not change.



- For example:-Laser light.
- Incoherent sources are those which sources of light which emit waves that have random frequencies and phase differences.
  - There is no relationship between the waves in terms of frequencies and phase difference.
  - For example:-Electric bulb, night lamp.

Coherent Source

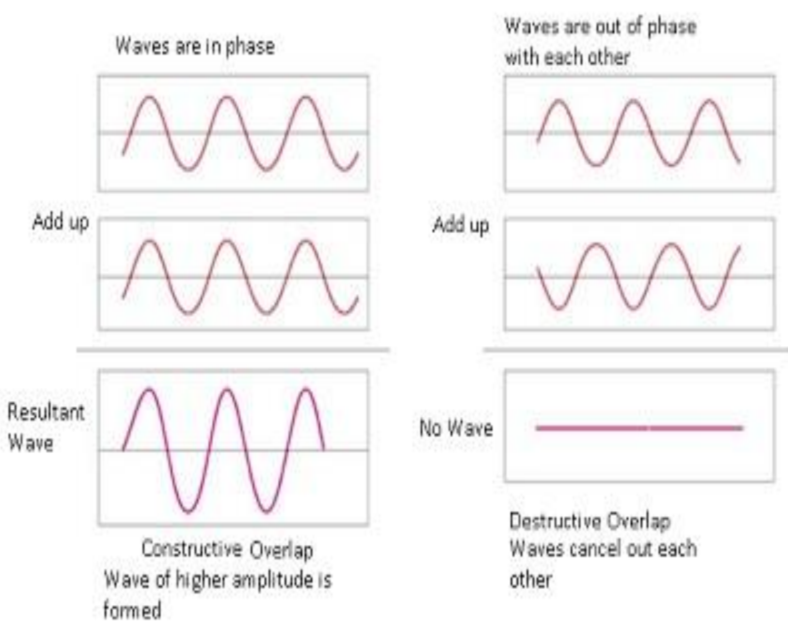


Incoherent Sources

Superposition of waves

- Superposition of waves is defined as the resultant displacement produced by a number of waves is the vector sum of displacements produced by each of them.
- Two 2 different waves add up to form a single wave and whose displacement will be given by vector sum of individual waves.
- There are 2 types of superposition:-
    - Constructive overlap:-When two waves overlap to produce a bigger wave that is known as constructive overlap.
        - Either two crests or two troughs overlap to form a bigger wave.
        - For constructive overlap both the waves are in phase with each other.

Destructive overlap:-There will no resultant wave when 2 out of phase waves overlap together.



Constructive Overlap

- Case 1:-
    - Consider two coherent sources S_1 and S_2emitting light waves of same frequency and constant phase.
    - The wave fronts of both the sources will overlap with each other.
    - Consider a point P as in the figure to calculate the intensity of disturbance.
    - The distance of point P from S_1 and S_2 is same. Therefore $S_1P=S_2$
    - Let the light wave emitted by wave at S_1 $y_1=a\cos\omega t$
        - Where a=amplitude of the wave,y_1 =displacement of the wave and cosωt =phase.

Light wave emitted by at S_2 $y_2=a\cos\omega t$

Intensity of both the waves $=I_0 \propto a^2$ (equation (1))

Resultant displacement of the wave formed by the superposition of the waves

- $\mathbf{y=y_1+y_2=2a\cos\omega t}$

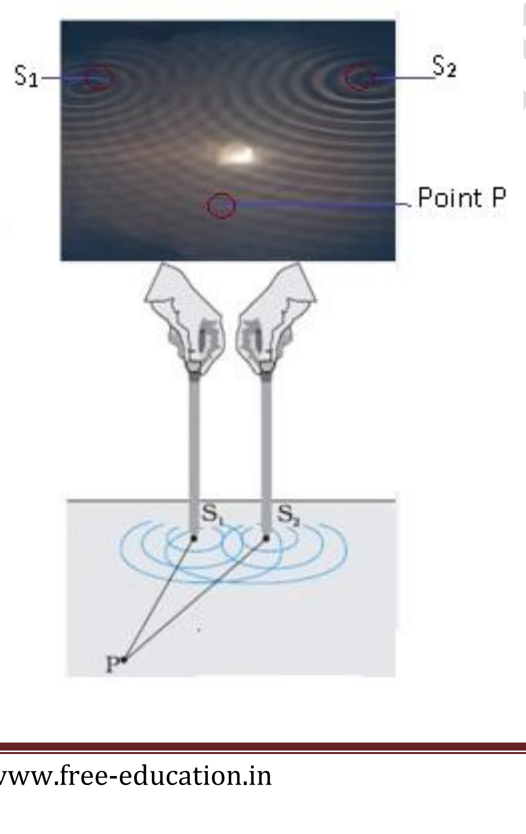
Intensity I ∝ $(\text{Amplitude})^2$

$I \propto (2a)^2 \Rightarrow I \propto 4a^2$ where Amplitude=2a.

$\mathbf{I=4\,I_0}$ using equation(1)

This means the intensity at point P will be four times the intensity of the individual sources.

S_1 and S_2two sources of light waves



- **Conclusion**: -
    - If a point is equidistant from two sources then the
        - Amplitude as well as the intensity increases.

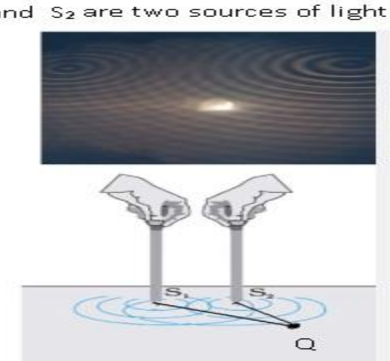
Path difference is defined as the difference in the paths from both the sources to a particular point.

- This implies S_2P - S_1P =0.
- If the path difference is 0 then it will be constructive overlap.

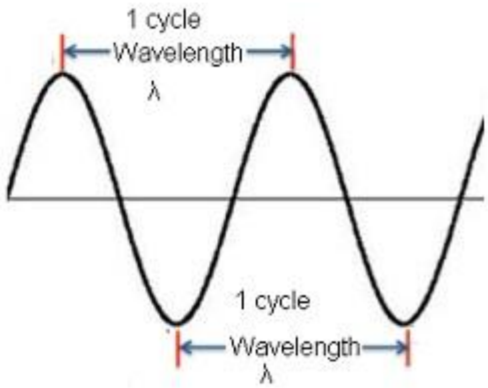
Case 2:- Considering a point Q which is not equidistant from the 2 sources and the path difference S_1Q - S_2Q = 2λ(integral multiple)

- => As $S_1Q > S_2Q$ therefore the waves originating from S_1 have to travel a greater path than S_2.
- Therefore waves from S_2 will reach exactly 2 cycles earlier than waves from S_1. Waves reach at S_2early by 2λ as compared to S_1.
- One cycle corresponds to λ and two cycles correspond to 2λ.
- Let the light wave emitted by wave at S_1, y_1=a cosωt
    - Where a=amplitude of the wave,y_1 =displacement of the wave and cosωt =phase.
- Light wave at S_2, y_2=acos(ωt -4 π) =a cosωt
    - (Path difference)λ =>2 π (phase difference),therefore 2λ=4π**.**
    - This shows y_1 and y_2 are in phase with each other.
    - Resultant y=y_1+ y_2 =2acosωt.
- This shows constructive overlap happened when the path difference is 0 or when it is 2λ.
- The intensity **I =4I$_0$**.
- **Path difference =n λ**; where n=0, 1, 2, 3…

S₁ and S₂ are two sources of light waves



Waves from S₂ will reach earlier than waves from S₁



Destructive overlap

- S_1R-S_2R=-2.5λ or S_2R - S_1R =2.5λ
- This means the waves from S_1 will take exactly 2.5λ cycles earlier than S_2.
- It is non integral multiple of λ.
    - Let the light wave emitted by wave at S_1 , y_1=a cosωt
        - Where a=amplitude of the wave,y_1 =displacement of the wave and cosωt =phase.

Light wave emitted by S_2, y_2=acos(ωt+5π) = -a cosωt

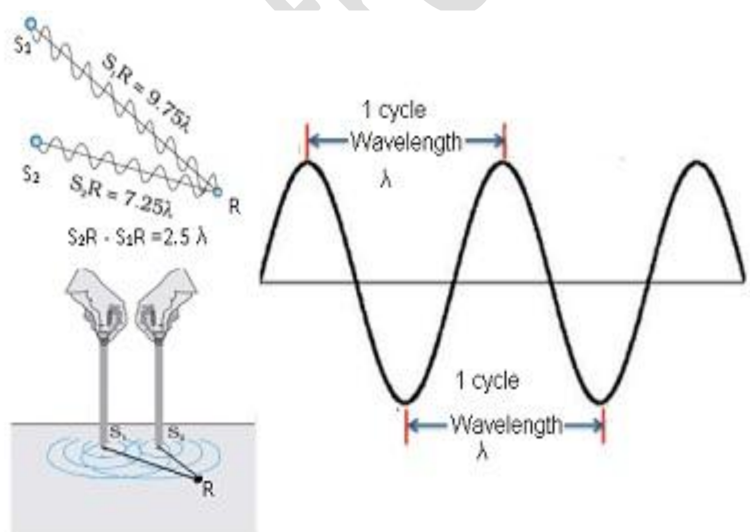
- (Path difference)λ =>2π(phase difference),therefore 2.5λ=5 π.

Therefore y=y_1+ y_2 =a cosωt – a cosωt =0.

Resultant Intensity **I=0**.

This shows when the path difference is non integral of λ then destructive overlap takes place and resultant intensity is 0.

Path difference=(n+(1/2)) λ



Coherent & Incoherent Addition of waves

- Consider 2 waves; first wave y_1=a cosωt and second wave y_2=a cos (ωt+Φ)
    - WhereΦ =phase difference between the 2 waves.
- Intensity of both the waves = I_0 and $I_0 \propto a^2$
- Resultant displacement y=y_1+ y_2 =a cosωt + a cos(ωt + Φ)
- =2acos(Φ/2) + cos(ωt+(Φ/2))
    - [using cosA + cosB=2cos((A+B)/2) +cos((A-B)/2)]
    - Where **amplitude = 2acos(Φ/2)**
- Also I $\propto 4a^2 \cos^2$(Φ /2) (becauseI ∝ $(\text{Amplitude})^2$)
- **I =4I_0 $\cos^2$ (Φ/2) where** $a^2=I_0$.

Conclusion:-

1.In case of constructive overlap path difference =nλ and phase difference Φ=0, (+-)2π, (+-)4π…

1. In case of destructive overlap path difference =(n+(1/2))nλ and phase difference =(+-) 3π,(+-) 5π…

Interference

- Interference is a phenomenon of superposition of 2 waves to form a resultant wave of greater, lower or the same amplitude.
- When the crest of a wave overlaps the crest of another wave of the same frequency at the same point, then the resultant amplitude will be the sum of the amplitudes of individual waves. Then it is known as constructive interference.
- Amplitude of the resultant wave will be more as compared to the amplitude of individual waves.
- When the crest of one wave meets the trough of another wave,then the resultant amplitude is given as difference of the two individual amplitudes.Then it is known as destructive interference.
- Amplitude of the resultant wave will be less as compared to the amplitude of individual waves.
- For example:-
    - If two stones are dropped in the river,ripples or wavesare generated by both stones.When both the waves overlap,there will be maximum displacement when the waves are in phase and there will be no displacement when they are out of phase.

Young's double slit experiment (YDSE)

The Young's experiment shows that matter and energy can display both wave and particle characteristics.

Purpose of double slit experiment is as follows:-

1. In order to prove the wave nature of light.
2. To explain the phenomenon of interference.

Two coherent sources of light were taken in order to maintain the 0 or constant phase difference between the sources of light.

- <u>Experimental set-up1:-</u>
    - Young took an ordinary source of light(S) such as light bulb.
    - The light was made to pass through a very small slit S (which was comparable with the wavelength of light).
    - The light coming from Source S was made to pass through two small slits S_1 and S_2 which were separated by a very small distance d.
    - One screen was kept in front of these 2 sources.

<u>Observation1:-</u>

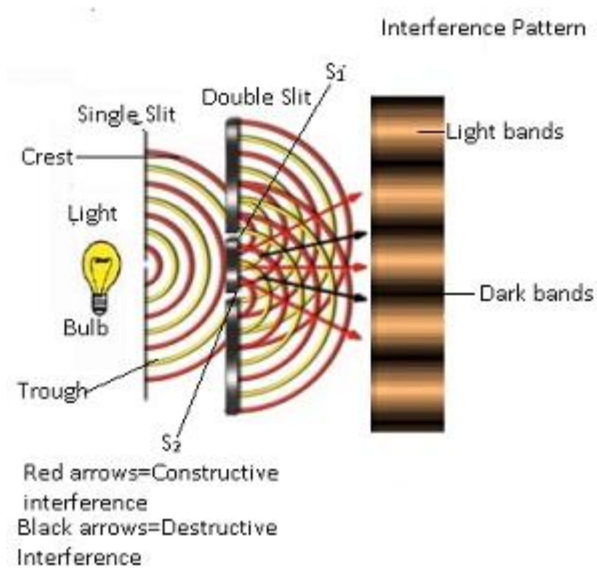
- He observed alternate dark and light bands were formed on the screen.

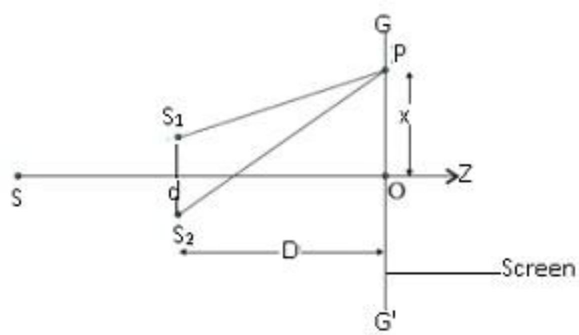
<u>Setup 2:-</u>

- Now he took 2 light bulbs i.e. 2 non coherent sources of light and placed a screen in front of them.

<u>Observation 2:-</u>

- He observed there were no alternate bands of light formed on the screen.
- Conclusion:-
- When coherent sources of light were taken then the phenomenon of interference is taking place.
- When non-coherent sources were taken phenomenon of interference was not taking place.
- The source S illuminated the sources S_1 and S_2 as a result the light from S_1 and S_2 become coherent.
- S was the source of bothS_1 and $S_{2,}$ therefore if there is any change in the phase of the source there will be change in the both sources also.
- Therefore both S_1 and S_2 will be always in phase with each other.

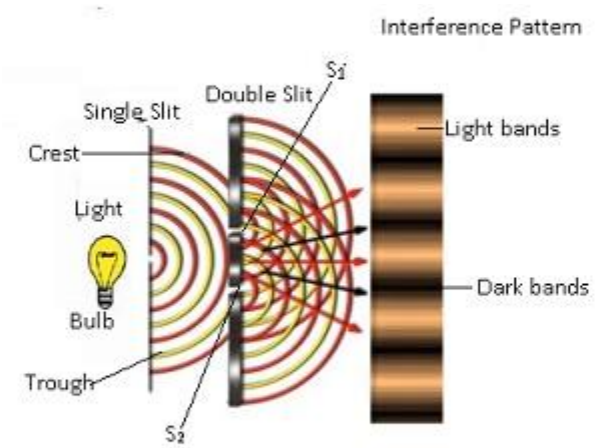




Why alternate sources of light bands were seen

- When the ordinary light source was made to pass through small slit then the wavefront of semicircle shape will be formed.
- Wavefronts are in semicircle shape because of obstacles on both the sides.
- In the figure red bands represents crests and yellow represents troughs.
- When these wavefronts passes through the 2 small slits again the wavefronts will arise.
- There will be points where red and yellow will also overlap with each other.
- Red + Yellow and Yellow + Red à Destructive interference à Intensity low
- Yellow + Yellow and Red + Red à Constructive interference à Intensity high
- Because of constructive and destructive interference there are alternate dark and light bands seen on the screen.
- **Conclusion**: -
  - When the light wave is originating from the 2 coherent sources they overlap with each other both constructively and destructively.

- As a result alternate light and dark bands of light is shown on the screen.
- This phenomenon of overlapping of light waves giving rise to regions of higher amplitude and regions of lower amplitudeis known as interference.
- Interference is a property related to the wave nature of the light.
- Young's Double slit experiment proved that the light is of wave nature which was proposed by Huygens principle.

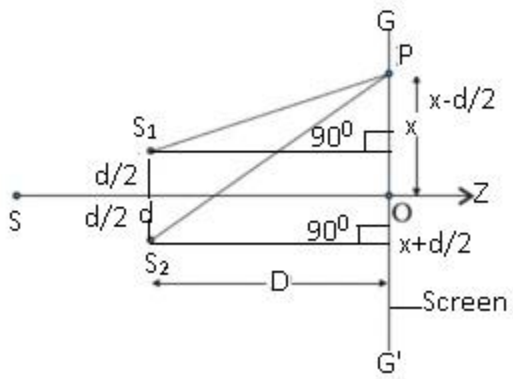


- Important resultsdrawn from the above experiment:-
- Bands were formed as a result of interference and interference was due to the overlapping (either constructive or destructive) of waves.
- Constructive and destructive overlapping depends on the path difference.
- If the path difference is integral multiple of λ = constructive interference.
- If path difference is non integral multiple of λ =destructive interference.

Calculation of path difference

- Let S_1 and S_2 are the sources and consider a point P where we have to calculate the intensity.
- Path difference = S_2P-S_1P
- Using Pythagoras theorem :- $(S_1P)^2 = D^2 + (x-(d/2))^2$ equation(1)
  - Where D=distance of the screen from 2 slits, x= position of the point where intensity has to be found.
- Similarly $(S_2P)^2 = D^2 + (x+(d/2))^2$ equation(2)
  - Where d=distance between the 2 small slits.
- Subtracting (2) and (1) => $(S_2P)^2 - (S_1P)^2 = (x+(d/2))^2 - (x-(d/2))^2$
- On simplifying $(S_2P)^2 - (S_1P)^2 = 2xd$
- => $(S_2P+S_1P)(S_2P- S_1P)=2xd$
- =>$(S_2P- S_1P) =(2xd)/(S_2P+S_1P)$
- If d<<D ; x<<D(screen is placed quite far away from the slit arrangement)

- => (S_2P+S_1P) (are almost same as D).
- => S_2P+S_1P =2D
- Therefore ($S_2P- S_1P$) = (2xd)/(2D)
- **Path difference =(xd)/(D)**Equation(2)



Observation:-

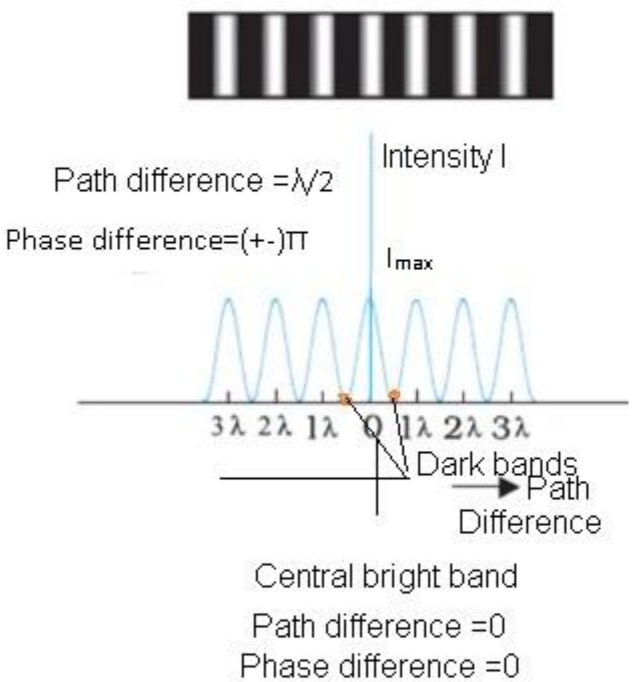
- Light from coherent sources produced alternate dark and bright bands on the screen placed some distance away from it.

Fringe Pattern

- The alternate dark and red bands which are obtained on the screen are known as fringe pattern and the alternate dark and bright bands are known as fringes.
- **<u>Bright Bands:-</u>**
  - Bright bands are formed as a result of constructive interference and they are the positions of maximum intensity.
  - Condition for maximum intensity:-
    - Path difference =n λ.
    - =>(xd/D) = nλ using Equation(2)
    - =>$\mathbf{x_n = ((n\,\lambda\,D)/d)}$ where x_n=position of n^{th} bright band.
      - When n=0 then it will be <u>central bright band</u>.
    - **<u>Dark Bands:-</u>**
      - Dark bands are formed by the destructive interference and they are the positions of minimum intensity.
      - Condition for destructive interference:-
      - Path difference =(n+(1/2))λ
      - => (xd/D) = (n+ (1/2)) λ.
      - =>$\mathbf{x_n=(n+ (1/2))\,(\lambda D/d)}$

- Where x_n=position of n^{th} dark band.

Graphical representation of fringe pattern



Fringe width:-

1. Fringe width is the distance between consecutive dark and bright fringes.
2. It is denoted by 'β'.
3. In case of constructive interference fringe width remains constant throughout.
4. It is also known as linear fringe width.

Angular Fringe width:-

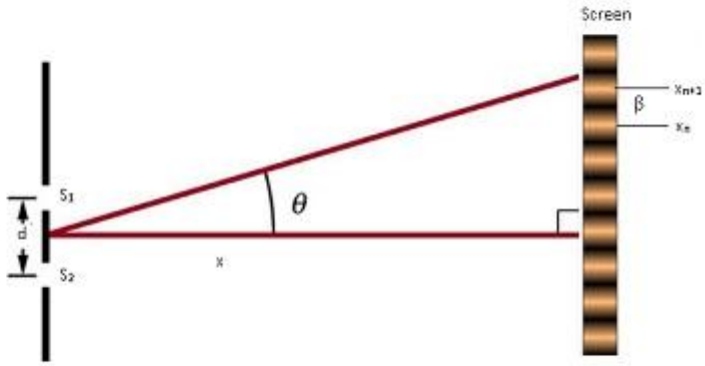
1. It is the angle subtended by a dark or bright fringe at the centre of the 2 slits.
2. It is denoted by 'θ'.

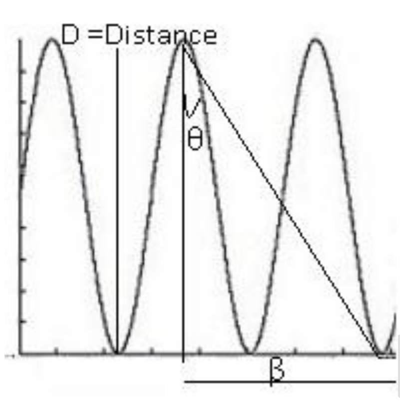
- Mathematical Expression for fringe width(β):-
  - x_n =((nλD)/d)
  - x_{n+1} =(((n+1)λD)/d)
  - β =x_{n+1} - x_n
  - =(((n+1) λD)/d) – ((nλD)/d)
  - =>**β = (λD/d)**
  - Therefore fringe width depends on:-

- (λ)Wavelength of the light used, (D) distance of the screen from the slits and (d) distance between two slits.

Mathematical Expression for angular fringe width(θ):-

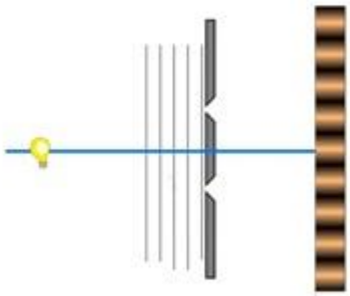
- $\theta = (\beta/D)$
- $\theta = (\lambda D)/(d\ D)$
- $\boldsymbol{\theta = (\lambda/d)}$

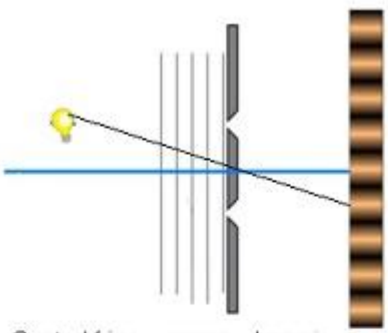




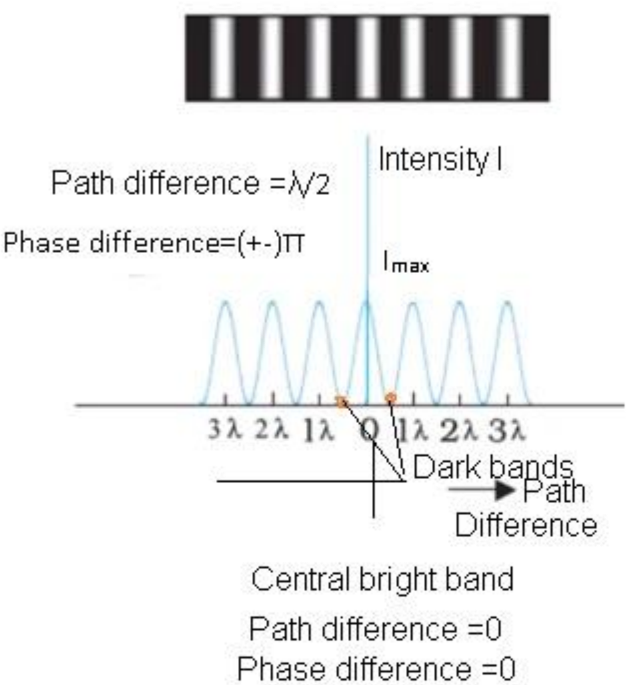
Conclusion of Young's double slit experiment

1. Central fringes gets shifted by – θ if the source gets shifted by θ.
   1. If the source S is shifted by some angle θ, there will be no change in fringe pattern. The central fringe will get shifted in the opposite direction.
2. Intensity of the fringes increase if point sources are replaced with slits.
   1. If there are slits instead of point source then more light waves will be able to pass through the slits.
   2. As a result stronger wavefronts are formedwhich give rise to even greater intensity fringes.





Central fringe moves when source moves



Problem:- In a Young's double-slit experiment, the slits are separated by0.28 mm and the screen is placed 1.4 m away. The distance betweenthe central bright fringe and the fourth bright fringe is measuredto be 1.2 cm. Determine the wavelength of light used in theexperiment.

Answer:- Distance between the slits, d = 0.28 mm = 0.28×10^{-3} m

Distance between the slits and the screen, D = 1.4 m

Distance between the central fringe and the fourth (n = 4) fringe,

u = 1.2 cm = 1.2×10^{-2} m

In case of a constructive interference, we have the relation for the distance between thetwo fringes as:

u =(n λD)/(d)

Where, n = Order of fringes

= 4 λ = Wavelength of light used

Therefore, λ= (ud/nD)

= $(1.2 \times 10^{-2} \times 0.28 \times 10^{-3})/(4 \times 1.4)$

=6×10^{-7}

=600nm

Hence, the wavelength of the light is 600 nm.

Problem:- In Young's double-slit experiment using monochromatic light of wavelengthλ, theintensity of light at a point on the screen where path difference is λ, is K units. What isthe intensity of light at a point where path difference is λ /3?

Answer:- Let I_1 and I_2 be the intensity of the two light waves. Their resultant intensities can be $I' = I_1 + I_2 + 2\sqrt{I_1 I_2} \cos\phi$ obtained as:

Where,

ϕ = Phase difference between the two waves

For monochromatic light waves,

$I_1=I_2$

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

$=2 I_1 + 2I_1\cos\phi$

Phase difference =(2π/λ) x Path difference

Since path difference = λ,

Phase difference,ϕ =2π

Therefore, $I' = 2 I_1 + 2I_1 = 4I_1$

Given,

I' = K

Therefore, $I_1 = (k/4)$ (equation (1))

When path difference= λ /3,

Phase difference ϕ = (2π/3),

Hence, resultant intensity,

$I_R = I_1 + I_1 + 2\sqrt{I_1 I_2} \cos(2\pi/3)$,

$= 2I_1 + 2I_1(-1/2) = I_1$

Using equation (1), we can write:

$I_R = I_1 = (k/4)$

Hence, the intensity of light at a point where the path difference is λ /3 units is (k/4) units.

Sustained Interference

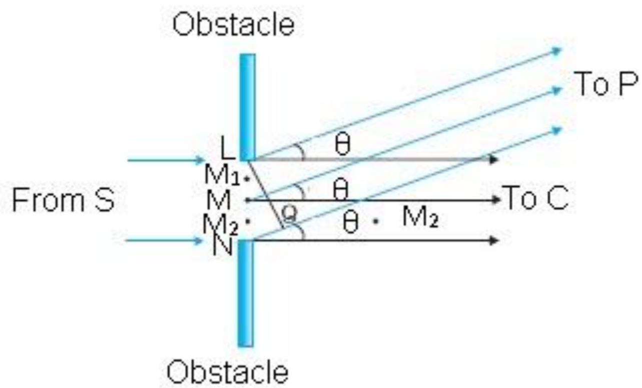
- Sustained interference means positions of maxima and minima of light intensity remain fixed throughout the screen.
- The intensity of the light remains same throughout.
- In case of sustained interference the phenomenon of interference is permanent.
- Therefore sustained interference is also known as permanent interference.

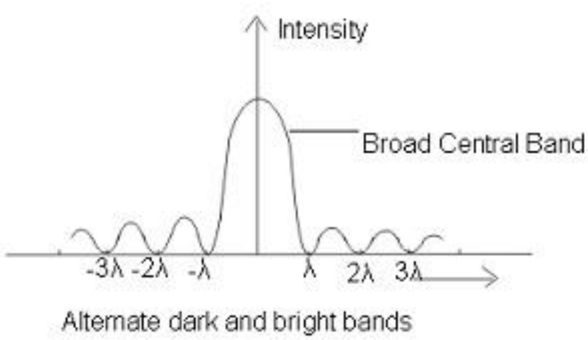
Conditions for sustained interference:-

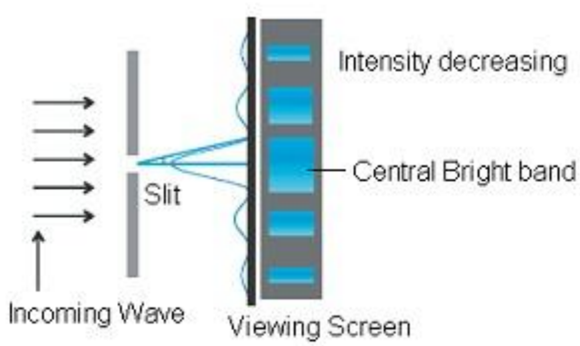
- Sources should be coherent.
    - If the sources are not coherent then there will no fixed pattern of constructive and destructive interference.
    - Sources should be very close to each other.
    - Sources should be point sources.
    - If the sources are not point then the distinction between bright and dark bands won't be clear.
    - Amplitudes from sources should be equal.
    - If amplitudes are not same then the intensity of the pattern formed will also vary. It won't be fixed.

Diffraction

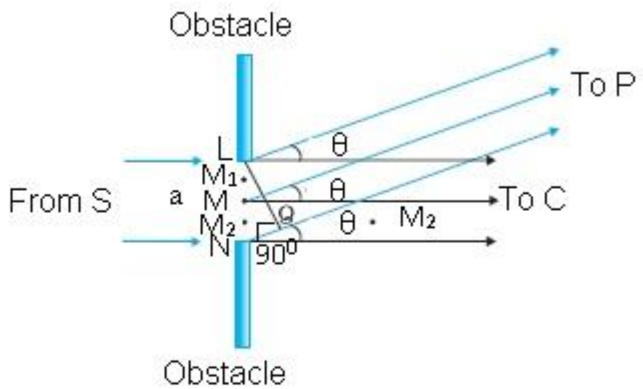
- Diffraction is the phenomenon by virtue of whichlight bendswhile passing through aslit or an opening.
- The extent of bending depends upon the diameter of the slit.
- Both Interference and Diffraction are closely related to each other.
- Young replaced the two slits by a single slit in his single slit experiment.Therefore this experiment is also referred as Young's single slit experiment.
- When the light passed through one slit a different type of pattern was observed on the screen.
- The pattern which was observed had a central maximum band and which was very wide as compared to interference pattern.
- There were alternate dark and bright bands and their intensity was decreasing on both the sides.

- The central maxima,was very wide whereas corresponding secondary maxima and minima were reduced in the intensity.
- The change in the pattern was formed due to diffraction instead of interference.
- <u>Conclusion:</u>-
- Broad central bright band.
- Alternate dark and bright bands on either side.
- Intensity was decreasing on both sides.
- 

- 

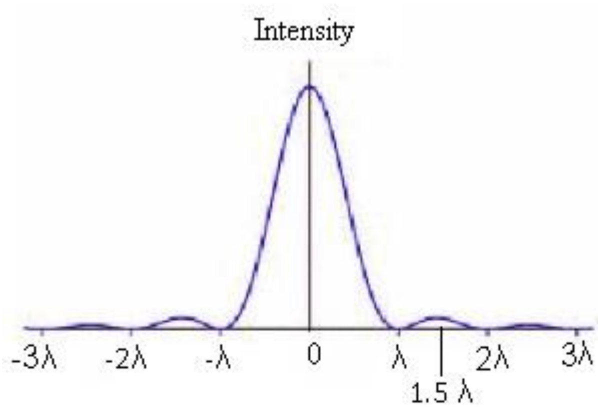
- **<u>Diffraction Fringe Pattern</u>**
- In diffraction there is an incoming wave which passes through a single slit and as a result diffraction pattern was obtained on the screen.
- 

- **<u>Diffraction pattern Maxima</u>**

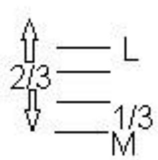
- The incident wavefront is parallel to the plane of the slit. This shows they are in phase with each other.
- From the given figure:-
- Path difference =NP – LP
- =>NQ = a sinθ where a=width of the slit.
- The slit was divided into smaller parts M_1, M_2, N and L, and when contribution from each part is added up.
- At the central point θ =0. This implies path difference =0.
- This means all the parts of the slit will contribute completely. Therefore the intensity is the maximum.
- **Central Maximum occurs at θ =0.**
- 

- **Problem:-**The light of wavelength 600nm is incident normally on a slit of width 3mm.Calcluate the linear width of central maximum on a screen kept 3m away from the slit?
- **Answer:-**
- Wavelength λ =600nm =600 $x10^{-9}$m.
- Width of the slit a =3mm=$3x10^{-3}$m.
- Distance of the screen D=3m.
- Condition for minima:-a sinθ =nλ
- =>a sin θ =λ
- =>sin θ = (λ/a) = (600 $x10^{-9}$)/ ($3x10^{-3}$)
- =>θ =(600 $x10^{-9}$)/($3x10^{-3}$)
- =>(x/D) = (600 $x10^{-9}$)/ ($3x10^{-3}$)
- => x= (600 x 10^{-9} x3)/ (3 $x10^{-3}$)
- x=600 x 10^{-6}m.
- Therefore width =2x = 1200 x 10^{-6}m
- Width = 1.2 mm
- **Diffraction pattern Secondary Maxima**
- Scientist Fresnel found that secondary maxima occurred when the value of θ is:
- **θ =(n+(1/2)) (λ/a)**
- For n=1 =>θ =(3λ)/(2a) = (1.5λ/a) (equation 1)
- Where = (3λ)/ (2a) it lies midway between 2 dark fringes.
- Suppose if the slit is divided into 3 parts ,

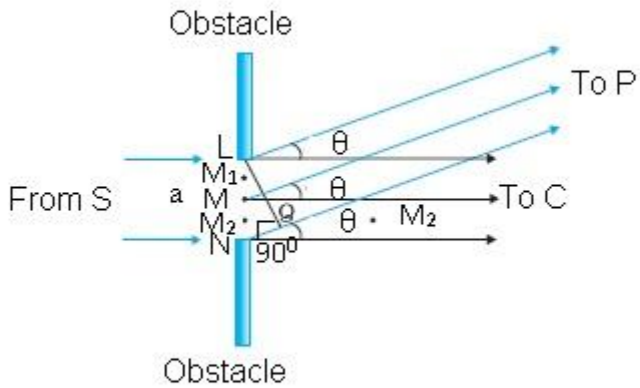
- Consider the first 2/3rd part of the slit ,
- Path difference = (2/3) a x θ
- =(2/3) a x(3λ/2a) using (equation 1)
- Path difference =λ.
- The λ is getting divide into 2 halves with path difference =λ/2 and λ/2.
- Each of λ/2 gets cancel with another λ/2.
- Contribution from (2/3rd) part gets cancel out with each other.
- Therefore only (1/3rd) contributes to I(Intensity).
- Intensity ≠ 0.
- Intensity is reduced.
- For n=2 => θ =(5 λ)/(a)
- Only (1/5th) part will contribute.
- For n=3 =>θ =(7 λ)/(2a)
- Only (1/7th) part contributes.



- Slit divided into 3 parts



- **<u>Diffraction pattern for Minima</u>**
- Condition to get minima on the diffraction pattern:
- **θ = (n λ/a)**; n= (+-) 1, (+-2)…
- For n=1, =>θ = (λ/a)
- Suppose the slit is divided into small parts. For every M_1in the portion LM there exists another M_2 in MN.
- From the figure it is clear that the contribution from all elements inLM (M_1) will cancel out the contribution from all elements MN (M_2).
- Therefore net intensity I=0 at θ = (λ/a).
- Minima occur at θ = (nλ/a). => aθ =nλ
- => a sinθ =nλ.

- Path difference = (nλ/a).
- Minima will occur at**a sin θ =n λ.** Where a =width of the slit,λ = wavelength of the light used.
- 

- **Problem:-** A beam of light consisting of two wavelengths, 650 nm and 520 nm, is used to obtaininterference fringes in a Young's double-slit experiment.
  (a) Find the distance of the third bright fringe on the screen from the centralmaximum for wavelength 650 nm.

  (b) What is the least distance from the central maximum where the bright fringes dueto both the wavelengths coincide?

  Answer:-
  Wavelength of the light beam, λ_1 =650nm
  Wavelength of another light beam,λ_2 =520nm
  Distance of the slits from the screen = D

  Distance between the two slits = d

  (a) Distance of the n^{th} bright fringe on the screen from the central maximum is given bythe relation, $x=n\lambda_1(D/d)$
  For third bright fringe, n=3

  Therefore x=3x650(D/d) =1950(D/d) nm

  (b) Let the n^{th} bright fringe due to wavelength and $(n-1)^{th}$ bright fringe due towavelength $\lambda_1$coincide on the screen. We can equate the conditions for bright fringesas:
  $n\lambda_2=(n-1)\lambda_1$
  520n=650n-650

  650=130n

  Therefore, n=5.

  Hence, the least distance from the central maximum can be obtained by the relation:

Note: The value of d and D are not given in the question.

Problem:- In a double-slit experiment the angular width of a fringe is found to be 0.2° on a screenplaced 1 m away. The wavelength of light used is 600 nm. What will be the angularwidthof the fringe if the entire experimental apparatus is immersed in water? Take refractiveindex of water to be 4/3.

Answer:-

Distance of the screen from the slits, D = 1 m

Wavelength of light used, λ_1 =600nm
Angular width of the fringe in air θ_1 =0.2°
Angular width of the fringe in water = θ_2
Refractive index of water, μ= (4/3)

Refractive index is related to angular width as:

$\mu = (\theta_1/\theta_2)$
$\theta_2 = (3/4)\theta_1$
$= (3/4)x0.2 = 0.15$

Therefore, the angular width of the fringe in water will reduce to 0.15°.

Problem:- A parallel beam of light of wavelength 500 nm falls on a narrow slitand the resulting diffraction pattern is observed on a screen 1 maway. It is observed that the first minimum is at a distance of 2.5mm from the centre of the screen. Find the width of the slit.

Answer:-

Wavelength of light beam, $\lambda = 500\text{ nm} = 500 \times 10^{-9}$ m
Distance of the screen from the slit, D = 1 m

For first minima, n = 1

Distance between the slits = d

Distance of the first minimum from the centre of the screen can be obtained as:

$x = 2.5\text{ mm} = 2.5 \times 10^{-3}$ m
It is related to the order of minima as:

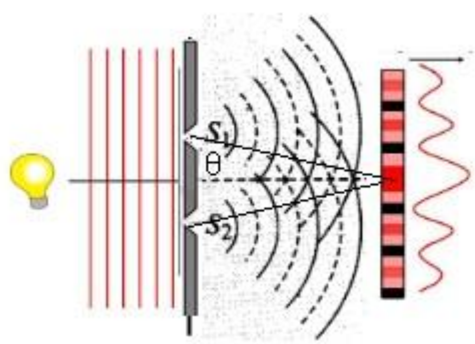
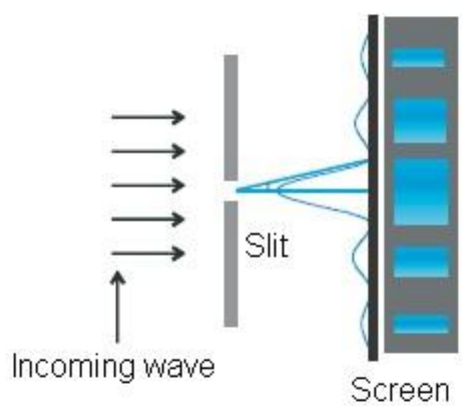
$n\lambda = x(d/D)$

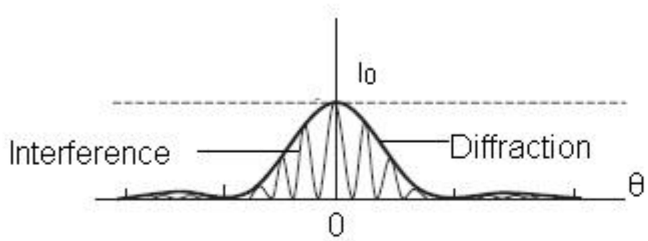
$d = (n\lambda D/x)$

$d = (1x500x10^{-9}x1)/(2.5x10^{-3}) = 2x10^{-4}$ m
d=0.2mm

Therefore, the width of the slits is 0.2 mm.

Interference and Diffraction

Interference	Diffraction
It is the superposition of two waves originating from the narrow slits.	It is the superposition of a continuous family of waves originating from each point on a single slit.
Pattern has a number of equally spaced bright and dark bands.	The central bright maximum is twice as wide as the other maxima.
There are 2 point sources. They cannot be split into smaller sources.	There is only one source. This source can be split into 'n' number of sources.
	



<u>**Interference & Diffraction: Conservation of energy**</u>

- Interference and diffraction phenomenon both obey the principle of conservation of energy.
- Light energy is neither lost nor gained. Light energy is redistributed.

- Total energy is conserved.

Resolving Power of Optical instruments

- Resolving power is defined as the inverse of the distance between two objects which can be just resolved when viewed through the optical instrument.
- Optical instruments should be able to display two separate images as distinct two separate images.
- Suppose if we are seeing 2 stars in the sky using telescope, and they are very closely placed to each other, they should not be displaced as one star.
- Instead they should be displaced as two separate stars. The ability to see them as separate 2 stars is known as resolving power.
- For example: -
    - Consider 2 rooms one is lit and another is dark.The room which is lit we are able to see everything clearly whereas in second room we are not able to see properly.
    - This is because the resolving power with which we are viewing second room is not good.
- If the resolving power is better the image will be clearer.So everything can be seen clearly.

Resolution	Magnification
It is possible to view 2 closely spaced objects clearly.	It is to magnify the size of objects.
It is the distinctness of 2 different objects.	It is to enlarge two different objects.

- Note:-
    - Whenever magnification increases the resolution decreases.
    - Resolution à Clarity or distinctness of two different objects.
    - Magnification à Enlargement of the size of an object.

Diffraction in resolving power of telescope

- In telescope resolving power plays an important role.
- In telescope there are 2 lenses one is objective lens and other is eye-piece.
- The purpose of objective lens to create an image at the second focal length of the objective and the first focal length of eyepiece.
- The image which iscreated will be inverted and diminished.

- The purpose of eye-piece is just to enlarge the image formed by the objective lens at the focal length.
- The purpose of objective lens is to resolve images as distinct.
- For example: -
  - If we are viewing 2 different stars the purpose of objective lens will be to resolve the stars as 2 distinct stars.
- Whenever a ray of light passes through the objective lens it should get focus at a particular point.
- But because of the phenomenon of diffraction instead of focussing at a specific point the image gets focussed in and around that area.
- Limit of Resolution :
  - Limit of resolution is defined as the angle subtended by the distant objects on the objective.
  - This means how small an object can be resolved by the telescope.
  - It is denoted by $d\theta$.
- Case 1:-The limit of resolution is 0.2 radians.
  - That is telescope can resolve up to 0.2 radians.
- Case2:- The limit of resolution is 20 radians.
  - The telescope can resolve up to 20 radians.
- Lesser the limit of resolution better is the resolving power.
  - Resolving Power (R.P) $\propto (1/d\theta)$.
  - $d\theta \propto (\lambda/D)$
  - =>**Limit of resolution $d\theta = (1.22\ \lambda/D)$**
    - Where λ =wavelength of the wave, D =diameter of the objective lens.

If the diameter of the objective lens is large then more and more light can pass through it.

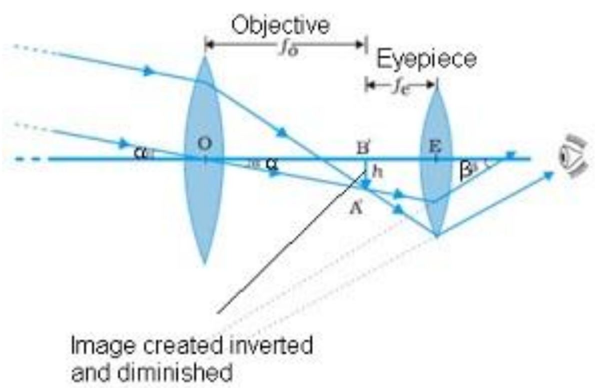
As a result telescope will be able to give more detailed image.

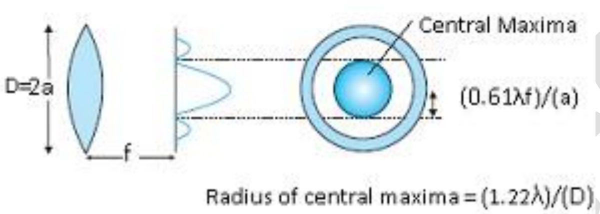
Resolving Power:

- Resolving power is defined as the relationship between limit of resolution and resolving power.
- Resolving Power (R.P) $\propto (1/d\theta)$.
- $d\theta \propto (\lambda/D)$
  - Where diameter of the aperture of the convex lens D = (2a) and f=focal length of the lens.
- When a parallel beam of light is incident on the convex lens it should get focussed at one single point.
- But diffraction occurs when the distance measured is comparable to the wavelength of the light.

- Therefore instead of single point a spotappears. This spot appears because of diffraction.
- There will be one central maximum surrounded by dark band (minima) then secondary maxima and then secondary minima.
- Experimentally the radius of Central maxima= $(1.22\lambda/D)$.
- P of a telescope $\propto(D/1.22\lambda)$.

Conclusion:-A telescope must have a larger diameter objective for better resolution.





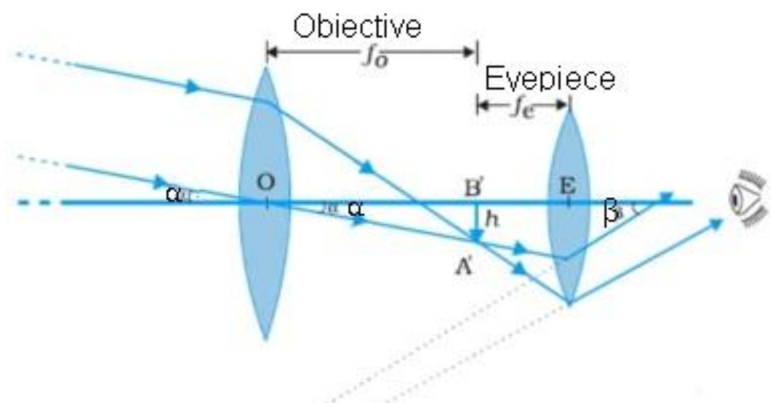
Diffraction in resolving power of Microscope

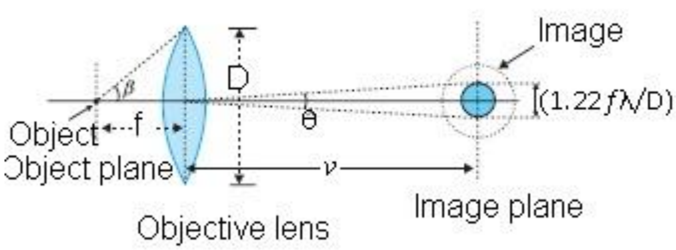
- In case of microscope resolving power helps to magnify the image.
- Resolution helps to distinguish between the small similar particles of an object when they are so closely placed with each other.
- When the distance between 2 points is comparable to the wavelength then diffraction occurs.
- Image formed due to the diffraction pattern vθ = v (22λ/D).
- The minimum distance for the object to be resolved is **v (22 λ)/(D)**andbeyond this point the object cannot be resolved.
- Minimum separation between objects to get resolved is given as:-
- d_{min} = (v (1.22λ/D))/m
  - Where m =magnification.
- d_{min}= (1.22λ/D) f;
  - Where f=focal length.
- tanβ = (D/2f)

- Whereβ = angle made by the objective lens at its focus, D=diameter and f=focus.

- **$\tan\beta = 1.22f\ \lambda$**
- Therefore $d_{min} = (1.22\lambda)/(\tan\beta)$
- $d_{min} = (1.22\lambda)/(2\tan\beta)$ if $\beta \approx$ small, $\tan\beta \approx \sin\beta \approx \beta$
- **$d_{min} = (1.22\ \lambda)/(2\sin\beta)$**
- Suppose if the medium between the object and the objective lens has refractive index n.
- $d_{min} = (1.22\lambda)/(2n\sin\beta)$ where $n\sin\beta$ = numerical aperture of objective lens.

- Therefore $d_{min} = (1.22\lambda)/(2n\sin\beta)$ is known as numerical aperture of the objective lens.
- Resolving Power(R.P) of a microscope $\propto (1/d_{min})$.
- This implies resolving power decreases as the distance increases.
- =>**P. =$(2n\sin\beta)/(1.22\ \lambda)$**
- Conclusion:-Resolving power can be increased by choosing medium of higher refractive index.





Validity of wave optics

- Consider a single slit of an aperture of thickness 'a'.Diffraction pattern will be observed.
- There will be centralmaxima due to diffraction.
- Angular size of central maximum = (λ/a)
  - where θ (condition to have central maximum)=(λ/a)

- The distance travelled by the light waves for the spread to occur = 'z'(the angular spread due to diffraction)
  - The spread is given as = (z λ/a)
  - Where (z λ/a) = a where a =width of the diffracted beam.

- **$z \approx (a^2/\lambda)$.** This distance is known as Fresnel distance.
- Fresnel distance describes the distance at which spread due to diffraction becomes comparable to the width of the slit or not.
- This is the boundary of ray optics and wave optics.
- For distances << z_f :
  - Spreading due to diffraction is smaller compared to size of the beam then the ray optics is valid.
- For distances >> z_f :
- Spreading due to the diffraction dominates over ray optics then the wave optics is valid.

Problem: Estimate the distance for which ray optics is good approximation for an aperture of 4 mmand wavelength 400 nm.

Answer:- Fresnel's distance (Z_F) is the distance for which the ray optics is a good approximation. Itis given by the relation,

$Z_F = (a^2/\lambda)$

Where,

Aperture width, a = 4 mm = 4×10^{-3} m

Wavelength of light, λ = 400 nm = 400×10^{-9} m

$Z_F = (4\text{x}10^{-3})^2/(400\text{x}10^{-9})$

Therefore, the distance for which the ray optics is a good approximation is 40 m.

Problem:- A slit 4cm wide is irradiated with microwaves of wavelength 2cm.Find the angular spread of central maximum, assuming incidence normal to the plane of the slit?

Answer:- Distance between the slits d=4cm,λ=2cm

The half angular speed of central maxima is given by,

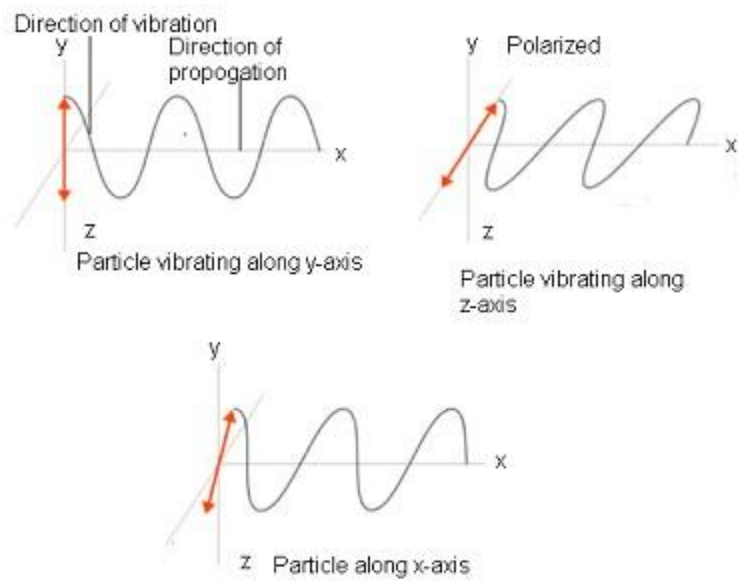
$d \sin\theta_1 = 1 \text{ x } \lambda = \lambda$

Therefore $\sin\theta_1 = (\lambda/d) = (2/4) = 0.5$

Or $\theta_1 = 30^0$.

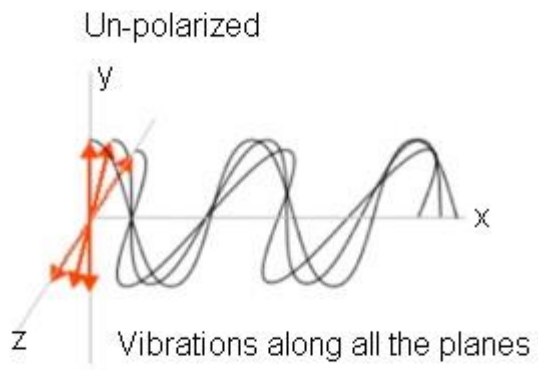
Polarizing and unpolarized light wave

- Polarized wave: - Polarized wave is defined as the vibration of the wave confined to specific plane.



1. In case of polarized wave the vibrations takes place in one plane not in multiple planes and it is perpendicular to the direction of propagation.
2. For example: -
    1. Vibrations of a rubber. It will vibrate randomly in all different directions. But when it is passed through a small slit then it will vibrate only in one plane.

- <u>Unpolarized wave</u>:-Unpolarized wave is defined as the plane of vibration which changes randomly in short intervals of time.
    - In case of unpolarized wave the vibrations takes place in multiple planes and it is perpendicular to the direction of propagation.



What is polarization?

Polarization is the process of transforming unpolarized light into polarized light.

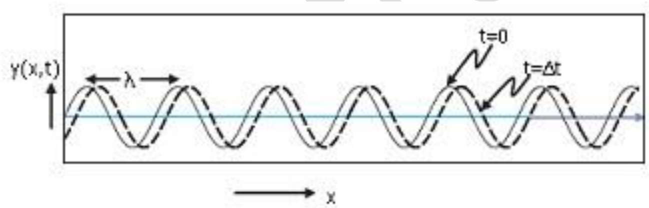
Methods of polarization:-

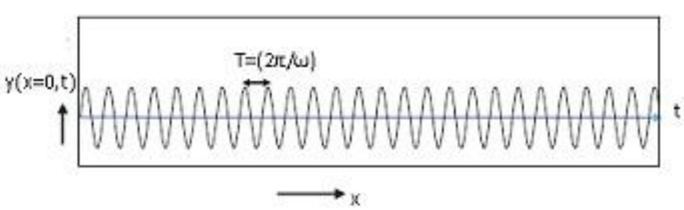
1. Polarization by Polaroid's
2. Polarization by Scattering
3. Polarization by Reflection
4. Polarization by Refraction

For example: - 3-D movies, sun glasses, photographic cameras.

Polarization: Transverse vs. Longitudinal waves

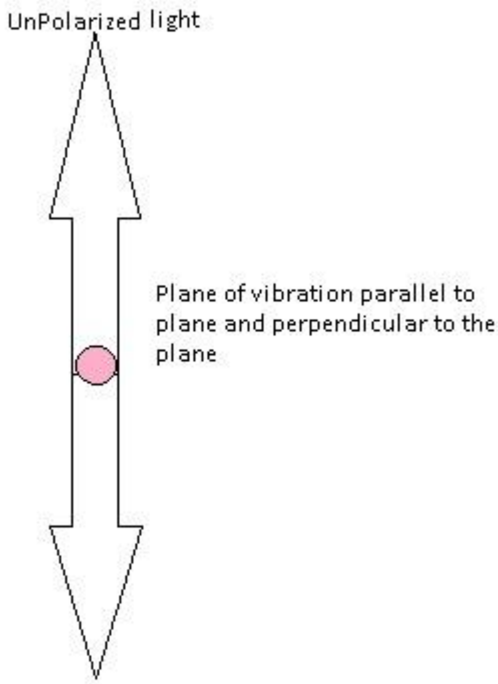
- In case of transverse waves there are many different ways in which particles can oscillate.
- Polarization is observed in transverse waves.
- In case of longitudinal waves there is only one direction in which particles oscillate.
- Therefore there is no polarized or unpolarized light in case of longitudinal wave.

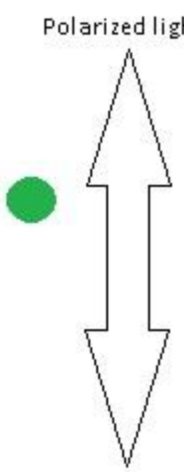


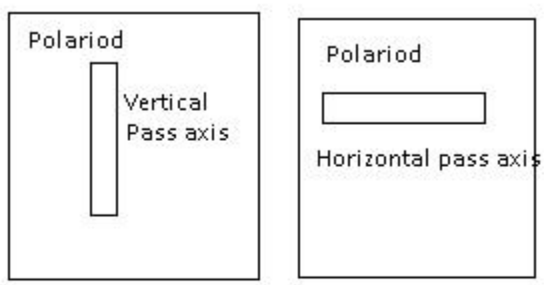


Polarization by Polaroid's

- Polaroids are polarizing materials consisting of long chain of molecules aligned in a particular direction.
- Polaroid's are in the form of thin sheets.
- Every Polaroid has pass axis. Pass axis is like a gate of aPolaroid which determines how the light will pass through it.
- There is horizontal as well as vertical pass axis.
- Unpolarized light on passing through a Polaroidit gets polarized.





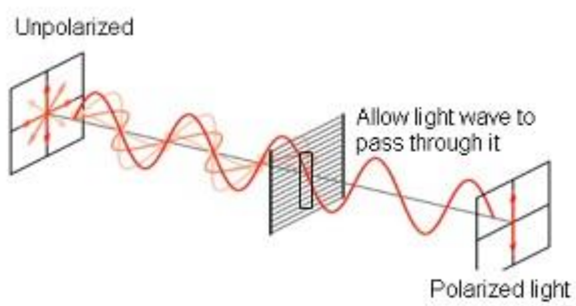


Experiment 1:-Polarization by a single polaroid (P1)

- When a beam of light passes through Polaroid was a polarized light.

Observations:

- The intensity was almost halved. As half of light rays were not allowed to enter only few were allowed to pass through it.
- Rotation of thePolaroid P1 has no effect on the intensity of transmitted light.
- There will be many different orientations but all are present in equal amount.
- Whatever is the direction of the Polaroidbut always the intensity of the lightcoming out of the Polaroid will be same.
- Sometimes it will allow vertically polarized light to pass and sometimes horizontal.



Experiment 2:-Polarization by a two polaroid (P1,P2)

- One more Polaroid(P2) was introduced in between the unpolarized light and Polaroid(P1).

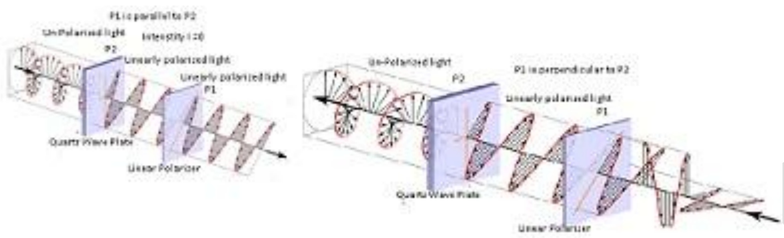
Observations:

- Intensity of the light is almost halved after P2.
- When the polarized light enters the second Polaroid (P1) then
    - If the pass axis of the polarizer P1 is along the same direction as P2 then the light will come out of the Polaroid P1.
    - Intensity will remain same.
- Rotation of the Polaroid P1 has effects on intensity of transmitted polarized light.
- When the two axes are not oriented in the same direction i.e. if the axis of the P1 is perpendicular to the axis of the P2.

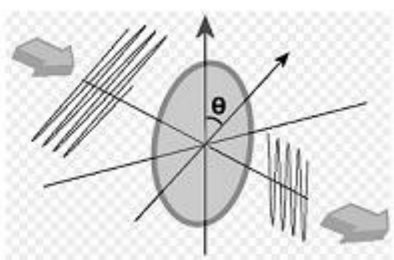
- Then P1 won't allow any light to pass through it as a result net intensity will be 0.
- <u>It concludes that :-</u>
  - Transmitted intensity=0 when pass axis of P1 is perpendicular to P2.
  - Transmitted intensity=maximum when pass axis of P1 is parallel to P2.

<u>Polaroid Experiment:Conclusion</u>

1. Intensity of the polarized light varies with the angle between the pass axes of the two Polaroid.
2. I =0 whenθ =90^0.
3. I =max when θ=0^0.
4. As the angle increases from 0^0 to 90^0 the intensity keeps on decreasing.



- **<u>Malus' Law</u>**: Malus' law explained when the angle between the pass axes be some arbitrary angle θ.
- Experimentally it was found that intensity varies as $\cos^2\theta$;
  - $\mathbf{I=I_0 \cos^2\theta}$.
  - Where θ =angle between the pass axes of two Polaroids, I_0=Intensity of polarized light after passing through P1 and I =new intensity after rotation.

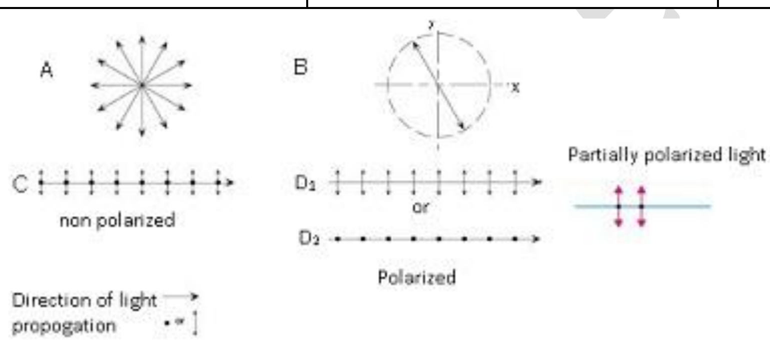


Polaroids: Applications

1. Sunglasses: -
   1. Sunglasses help to reduce the intensity of the sun light.
   2. Sunlight is unpolarized light so when it passes through the sun glass it becomes polarized.As a result intensity of sunlight is greatly reduced.
2. Photographic cameras:-
   1. In this type of cameras Polaroids are attached.
3. Car sun film:-
   1. Thin film reduces the intensity of the sunlight.

4. 3D glasses:-
    1. By using 3D glasses objects can be seen in 3 dimensional.
    2. There are 2 images slightly displaced with each other are formed by our 2 eyes.
    3. These images are then interpreted by the brain.In 3D glasses Polaroids are used.
    4. One glass will polarize in such a way that image is formed in particular orientation and other glass will polarize the image in another orientation.
    5. As a result these two orientations will be interpreted by the brain and image is formed.

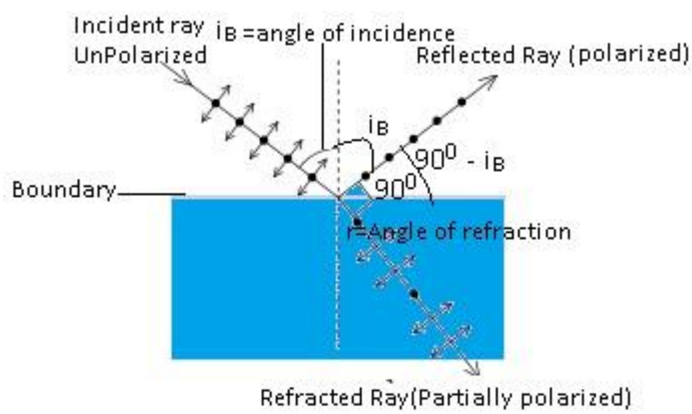
Unpolarized	Polarized	Partially polarized
Vibrations takeplace in any possible random plane.	Vibrations takeplace in one single specific plane.	It will have some polarized as well as some unpolarized components. It vibrates in vertical plane but sometimes it vibrates in horizontal plane.




Polarization by reflection and refraction

- When an unpolarized beam of light falls on boundary, reflected wave and refracted wave are partially polarized.
- An incident wave is an unpolarized light .Some of the rays will get reflected and some gets refracted.
- Most of the light waves that reflected were polarized waves, which were parallel to the plane.
- Most of the rays along the refracted ray were unpolarized waves with one or two polarized components.
- Refracted Ray à More unpolarized and Reflected rayà more polarized.
- If the angle of incidence varies more and more unpolarized light was able to pass through the surface.
- At one particular value of angle of incidence there was maximumpolarization in the reflected ray.
- Above and below the value of angle of incidence, both reflected and refracted rays were partially polarized.

Brewster's law:- Brewster's law states that at any particular angle of incidence, reflected ray is completely polarized; and the angle between reflected and refracted ray is 90^0.



- At $i = i_B$; where i_B = Brewster's angle of incidence.
- From Snell's law :- (sin i/sin r)= μ
- => $\sin i_B / (\sin(\pi/2 - i_B))$
- =>$(\sin i_B / \cos i_B) = \mu$
- **$\tan i_B = \mu$**

Problem:-

What is the Brewster angle for air to glass transition? (Refractive index of glass = 1.5.)

Answer:-

Refractive index of glass,μ=1.5

Brewster angle = θ

Brewster angle is related to refractive index as:

$\tan\theta = \mu$

$\theta = \tan^{-1}(1.5) = 56.31^0$

Therefore, the Brewster angle for air to glass transition is 56.31°.