1.1 INTRODUCTION

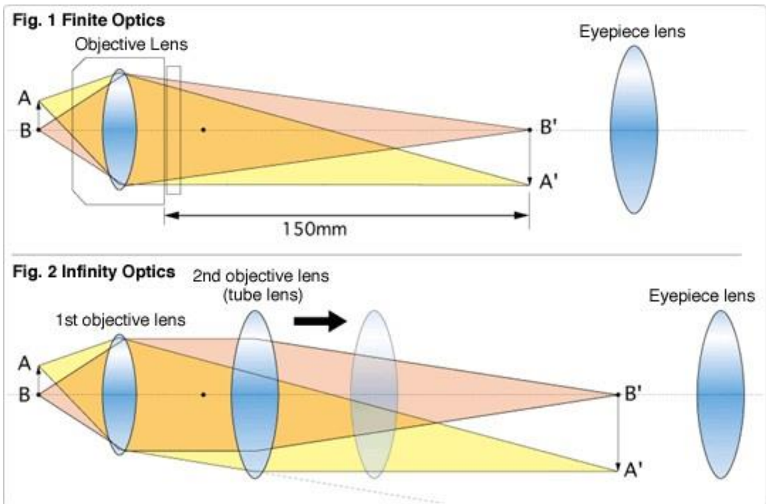
Light is a form of energy that enables us to see and perceive objects with our eyes. Scientifically, light is an electromagnetic wave of wavelength belonging to visible part (wavelength of 400 nm to 750 nm) of electromagnetic spectrum. We see objects either by the light they produce or by the light they reflect from other objects. Objects that produce their own light are said to be luminous. Examples are the sun, electric bulbs, candle light etc., whereas, non luminous objects do not produce their own light. We can see these objects only when light fall on them from other sources and it is thrown back or reflected into our eyes. An important example is that of the moon, which shines in the night because it reflects light coming from the sun and not because it is luminous.

Optics is the science or more specifically a branch of physics in which we study the behavior and properties of light. The study also includes the interaction of light with matter and construction of instruments that use or detect it. For the sake of convenience the subject of optics can be divided into two parts: (i) physical or wave optics, which deals with the wave nature of light. It accounts for optical effects such as diffraction and interference etc., and (ii) geometrical or ray optics, which deals with the formation of images by lenses and mirrors andtheir combinations on the basis of certain geometrical laws obeyed by light.

The present block of the course 'optics' is dedicated to the geometrical optics only hence, in the following sections, we will concentrate on its learning in detail.

Optics is the branch of physics which involves the behavior and properties of light, including its interactions with matter and the construction of instruments that use or detect it.

Optics usually describes the behavior of visible, ultraviolet, and infrared light. Because light is an electromagnetic wave, other forms of electromagnetic radiation such as X-rays, microwaves, and radio waves exhibit similar properties.



Newton's corpuscular theory of light

Newton's corpuscular theory of light is based on the following points

1. Light consists of very tiny particles known as "corpuscular".

2. These corpuscles on emission from the source of light travel in straight line with high velocity.

3. When these particles enter the eyes, they produce image of the object or sensation of vision.

4. Corpuscles of different colors have different sizes.

Huygens's wave theory of light

Christian Huygens proposed the wave theory of light. According to Huygens's wave theory:

1. Each point in a source of light sends out waves in all directions in hypothetical medium called "ETHER".

2. Light is a form of energy.

3. Light travels in the form of waves.

4. A medium is necessary for the propagation of waves & the whole space is filled with an imaginary medium called Ether

5. Light waves have very short-wave length.

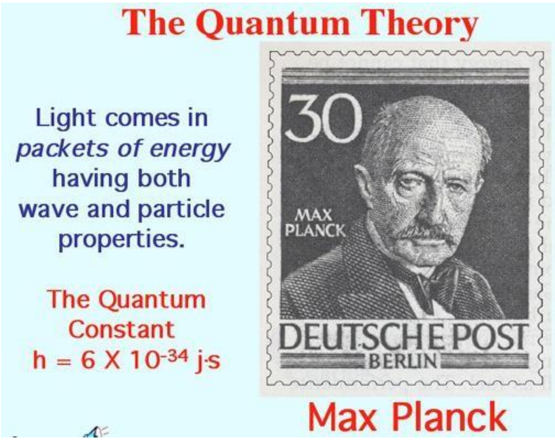
Quantum theory of light

Quantum theory was put forward by MAX-PLANCK in 1905. According to quantum theory

"Energy radiated or absorbed cannot have any fractional value. This energy must be an integral multiple of afixed quantity of energy. This quantity is called "QUANTUM"

Or

Energy released or absorbed is always in the form of packets of energy or bundles of energy. These packetsof energy are known as QUANTA or PHOTONS.



Geometrical optics describes light propagation in terms of rays. The rays are the approximate paths along which light propagates under certain circumstances. The basic assumptions of geometrical optics include, that light rays:

- Propagate in straight line paths in a homogeneous medium, called as rectilinear propagation.
- Bend, and in particular circumstances may split into two, at the interface between two dissimilar media
- Follow curved paths (iterative bending) in a medium in which refractive index changes
- May be absorbed or reflected at glossy surfaces

There are certain laws which explain the above assumptions. These laws form the basis of geometrical optics and are called *fundamental laws*. The fundamental laws are

1. The laws of rectilinear propagation of light
2. The laws of reflection of light
3. The laws of refraction of light

A general principle which covers all these laws is known as Fermat's principle of least time.

1.2 OBJECTIVES

After studying this unit, you will be able to:

- know Fermat's principle of least time
- familiarize with incident ray, reflected ray and refracted ray
- familiarize with angle of incidence, reflection and refraction
- state laws of reflection
- state laws of refraction- Snell's law
- define refractive index
- explain total internal reflection as a special case of refraction

1.4. FERMAT’S PRINCIPLE OF LEAST TIME

In 1658 Pierre De Fermat, a French mathematician enunciated the principle of least time in the following way:

A ray of light in passing from one point to another through a set of media by any number of reflections or refractions chooses a path along which the time taken isminimum or the least.

Based on this principle, the laws of rectilinear propagation, the laws of reflection and refraction can be derived (see section 1.5). However in some cases, it has been found that the time taken by light is not minimum but maximum or else it is neither maximum nor minimum but it is stationary. This is found in case of image formation by lenses, in which all rays starting from an object point, reaching to the image point; choose the path of maximum or minimum time. Therefore, the modified form of Fermat's principle of least time is known as Fermat's principle of stationary time or Fermat's principle of extreme path, which may be stated as follows:

A ray of light in passing from one point to another through a set of media by any number of reflections or refractions chooses a path for which the time taken is either minimum or maximum or stationary. The mathematical verification of this law is provided in the later sections.

1.5 APPLICATION OF FERMAT’S PRINCIPAL

On the basis of Fermat's principle you can derive laws of reflection and refraction.

1.5.1. Laws of Reflection

When light ray falls on a smooth polished surface separating two media, it comes back in the same medium, the phenomenon is called reflection and the boundary is called reflecting surface. The light obeys following two laws of reflection.

First law:

The incident ray, reflected ray and the normal to the surface at the point of incidence all lie in one plane. You can prove this law in the following way.

Let the plane ABCD be normal to the plane mirror shown in figure 1.1. *P* is point object imaged by mirror as *P'*. Consider a point *M'* on the plane mirror; but not on plane ABCD. Let a ray *PM'* be reflected as *M'P'*. Draw a normal *M'M* on plane ABCD. Point M is the foot of the normal on ABCD.

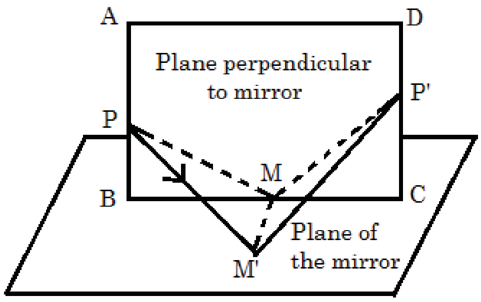


Fig. 1.1

Now, *PMM'* and *P'MM'* are right angle triangles. *PM'* and *P'M'* are respective hypotenuse. Therefore, we have

$$PM' > PM \quad \text{and} \quad P'M' > P'M$$

But Fermat's principle demands that the path followed must be the shortest, i.e., the light would not travel along *PM'P'*. As we shift *M'* towards *M* the path of light ray becomes shorter. It is seen that the shortest possible path is *PM P'*, where the point of incidence *M* lies on plane ABCD. PM and MP' are the incident and reflected rays. This proves the first law of reflection.

Second law:

For a smooth surface, the angle of incidence is equal to the angle of reflection. You can prove the second law as follows.

Assuming *DD'* is a reflecting plane shown in figure 1.2. Object *P* is imaged as *P'* and *M* is the point of incident. The normal to the plane at this point is *MN* and is shown by dotted line.

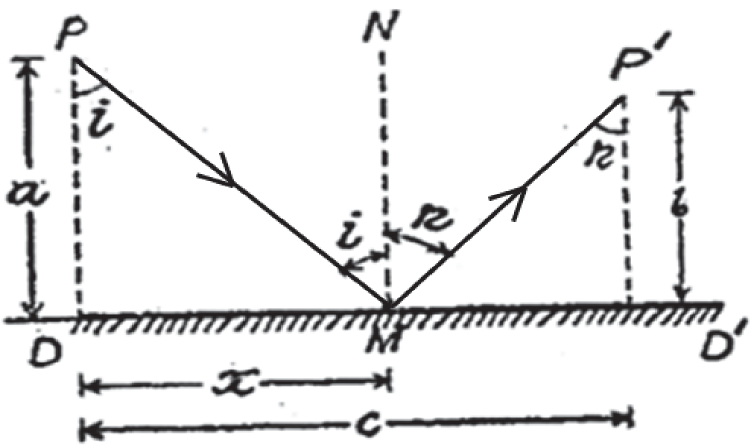


Fig. 1.2

PM and *MP'* are the incidence and reflected rays. Let *I* and *r* are the angles of incidence and reflection respectively. Let us suppose distances

$$PD = a,\ P'D' = b,\ DM = x,\ DD' = c.$$

The ray of light travels in air from *P* to *P'*. Let the path *PMP'* be *s*, then the total distance covered by light ray be

$$s = P\,MP' = PM + MP'$$

$$= \sqrt{(PD^2 + DM^2)} + \sqrt{(D'M^2 + D'P'^2)}$$

$$s = \sqrt{(a^2 + x^2)} + \sqrt{\{(c - x)^2 + b^2\}} \qquad \ldots\ldots\ (1.8)$$

It is evident that the path from P to P' remains the same even if the point of incidence M shifts. Shifting of M changes *x* only. According to Fermat's principle the path *PMP'* must be either minimum or maximum. It means that the differential coefficient of *s* with respect to *x* must be zero, i.e.

$$\frac{ds}{dx} = \frac{1}{2}\,\frac{2x}{\sqrt{(a^2 + x^2)}} - \frac{1}{2}\,\frac{2\,(c-x)}{\sqrt{\{(c-x)^2 + b^2\}}} = 0$$

or

$$\frac{x}{\sqrt{(a^2+x^2)}} = \frac{(c-x)}{\sqrt{\{(c-x)^2+b^2\}}}$$

From figure 1.2, we have,

$$\frac{x}{\sqrt{(a^2+x^2)}} = \sin i,\quad (c - x)/\sqrt{\{(c - x)^2 + b^2\}} = \sin r$$

∴ $$\sin i = \sin r \qquad \ldots\ldots\ (1.9)$$

or $$i = r$$

Hence you can see that the second law of reflection is derived from Fermat's principle. Further the second differential co-efficient of s, i.e., $\frac{d^2s}{dx^2}$ proves that the path is minimum (or path of least time).

1.5.2. Laws of Refraction

When a ray of light passes from one homogenous medium to another, the phenomenon of bending of light ray towards or away from the normal is called refraction. Again there are following two laws of refraction.

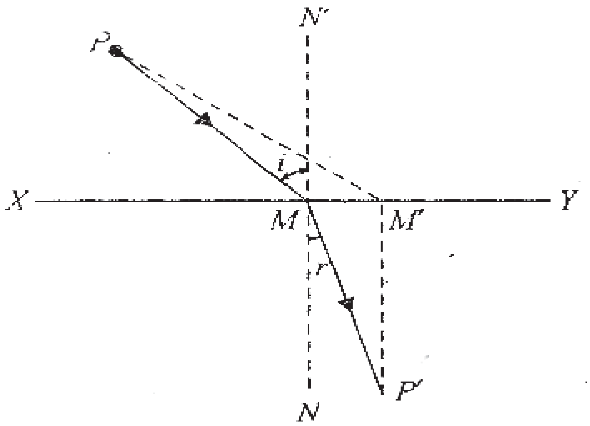


Fig. 1.3

First Law:

The incident ray, refracted ray and the normal at the point of incidence all lie in one plane.

Let us assume XY be a plane surface dividing two media shown in figure 1.3. A ray starting from point P is incident on M. It is refracted as MP' in the other medium, ∠i and ∠r are the angles of incidence and refraction. Let us assume that the ray follows path *PM'P'* instead of *PMP'*. It is evident that

$$PM' + M'P' > PM + MP'$$

Therefore, path *PM'P'* is not possible. If you shift *M'* towards *M*, the path from *P* to *P'* through M shortens. It is shortest when *M'* is coincident with *M* which is in accordance with Fermat's principle and proves the first law.

Second Law:

The ratio of the sine of angle of incidence to the sine of angle of refraction is aconstant for a given pair of media.

You can further prove that the ratio of the sin *i* to sin *r* is equal to the refractive index of second medium with respect to the first medium which is also known as Snell's law.

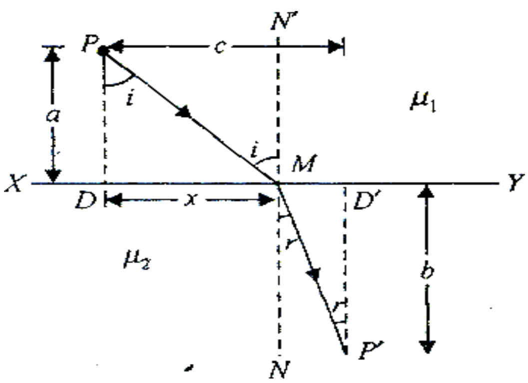


Fig. 1.4

In figure 1.4, XY is a plane surface dividing two media of refractive indices μ_1 and μ_2. Consider a point object *P* in the first medium, *PM* and *MP'* are the incident and refracted rays, *i* and *r* are the angle of incidence and refraction.

$$PD = a,\ DM = x,\ DD' = c,\ D'P' = b$$

If a ray of light travels a distance S in a medium of refractive index μ, than product μS is called the optical path in the medium. The optical path from P to P' is given by

$$S = PMP' = \mu_1 PM + \mu_2\, MP'$$

$$= \mu_1 \sqrt{(PD^2 + DM^2)} + \mu_2 \sqrt{(D'M^2 + D'P^2)}$$

$$= \mu_1 \sqrt{(a^2 + x^2)} + \mu_2 \sqrt{\{(c - x)^2 + b^2\}}$$

Now, for S to be minimum dS/dx must be zero and d^2S/dx^2 positive. Differentiating S with respect to x, we get

$$\frac{dS}{dx} = \frac{1}{2} \cdot \frac{\mu_1 x}{\sqrt{(a^2 + x^2)}} - \frac{\mu_2 (c - x)}{\sqrt{\{(c - x)^2 + b^2\}}} = 0$$

or
$$\frac{\mu_1 x}{\sqrt{(a^2 + x^2)}} = \frac{\mu_2 (c - x)}{\sqrt{\{(c - x)^2 + b^2\}}}$$

Using triangles *PMD* and *P'MD'*, you can write the above relation as

$$\mu_1 \sin i = \mu_2 \sin r$$

or
$$\frac{\sin i}{\sin r} = \frac{\mu_2}{\mu_1} = {}_1\mu_2 \qquad \ldots\ldots\ (1.10)$$

Where ${}_1\mu_2$ is the refractive index of the second medium with respect to the first medium. This is the **Snell's law** of refraction.

You can show that the second differential coefficient of S, i.e., $\left(\frac{d^2 s}{dx^2}\right)$ for the plane surface comes out to be positive. It proves that the second law of refraction is in accordance with Fermat's principle, i.e., the actual path is minimum or path of least time. But you will see that, this condition is satisfied in the case of plane surfaces only and not in the case of curved surfaces. For curved surfaces, the path may be a maximum or minimum.

1.5.3. Refractive Index

The refractive index is a relative property of two media. The refractive index of any medium with respect to free space (or air) is called the absolute refractive index. The absolute refractive index of any medium depends on its nature, wavelength of incident light and the temperature. The frequency of refracted ray remains the same as that of incident light, but its velocity and wavelength change. Let us now consider the following cases.

Case I:

If μ_1 and μ_2 are the absolute refractive indices of first and second media respectively and light ray enters from rarer medium to the denser medium then, we have, $\mu_2 > \mu_1$

∴
$$\frac{\sin i}{\sin r} = \frac{\mu_2}{\mu_1} > 1$$

or
$$\sin i > \sin r$$

or
$$i > r$$

This simply shows that refracted ray is deviated towards the normal.

Case II:

If light ray enters from denser medium to rarer medium, then $\mu_2 < \mu_1$

$$\therefore \qquad \frac{\sin i}{\sin r} = \frac{\mu_2}{\mu_1} < 1$$

or $$\sin i < \sin r$$

or $$i < r$$

Thus the refracted ray is deviated away from the normal

.

$${}_1\mu_2 = \frac{c_1}{c_2} = \frac{\lambda_1}{\lambda_2} = \frac{\mu_2}{\mu_1} = \frac{\sin i}{\sin r} = \frac{1}{{}_2\mu_1} = \sin\theta_c = \frac{c}{v}$$

Fig.1.7

Case III:

If i = 0, then r = 0, i.e., the incident light ray is along normal then the refracted ray passes undeviated, but its velocity gets changed.

The absolute refractive index can be defined in other ways also. The absolute refractive index of a medium is defined as the ratio of speed of light in the free space to the speed of light in medium. Accordingly, if c is speed of light in free space and v the speed of the light in the medium, then the refractive index

$$\mu = \frac{c}{v} \qquad \ldots\ldots. \quad (1.11)$$

In refraction the frequency of wave (υ) remains unchanged, therefore, c = $\upsilon\lambda$ and v = $\upsilon\lambda_m$. Where, λ_m is wavelength of light in medium. Thus refractive index of a medium may also be given by the expression,

$$\mu = \frac{\lambda}{\lambda_m} \qquad \ldots\ldots. \quad (1.12)$$

1.5.4. Total Internal Reflection

When a ray of light moves from denser to rarer medium, then the refracted ray is deviated away from normal (figure 1.8 (a)). With increase in angle of incidence, the angle of refraction increases. For a certain angle of incidence in denser medium, the corresponding angle of refraction in rarer medium is 90^0 (figure 1.8(b)).

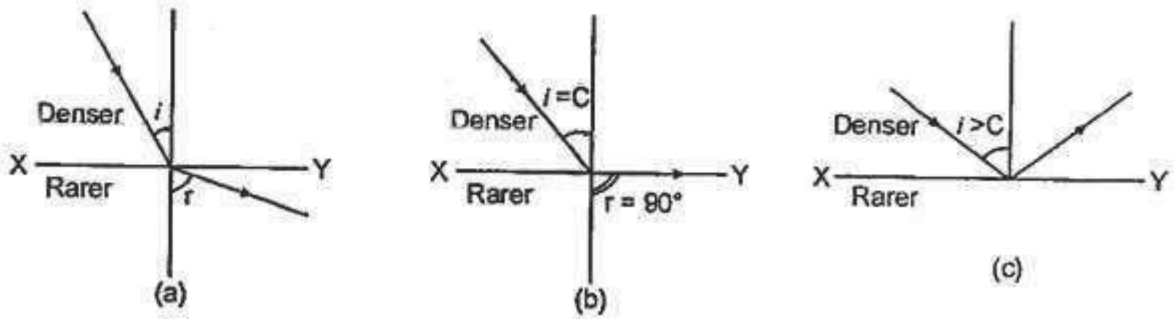


Fig. 1.8

This particular angle of incidence for which the corresponding angle of refraction is 90^0 is called the critical angle and is denoted by C. The value of the critical angle depends on the nature of the two media.

If angle of incidence is increased beyond its critical value, the incident ray is not refracted but returns back to denser medium [figure 1.8(c)]. This phenomenon is called **total internal reflection**.

Conditions of Total Internal Reflection

(i) The ray must pass from denser medium to rarer medium.

(ii) The angle of incidence in the denser medium must be greater than the critical angle for the given pair of media.

Relation between Refractive Indices of Media and Critical Angle

If μ_d and μ_r are the refractive indices of denser and rarer media respectively then fromSnell's law, we have,

$$\frac{\sin i}{\sin r} = \frac{\mu_r}{\mu_d} \qquad \ldots\ldots. \quad (1.13)$$

For critical angle of incidence, $i = C$ and $r = 90^0$

$$\therefore \qquad \frac{\sin C}{\sin 90^0} = \frac{\mu_r}{\mu_d} \quad \Rightarrow \sin C = \frac{1}{{}_r\mu_d} \qquad \ldots\ldots. \quad (1.14)$$

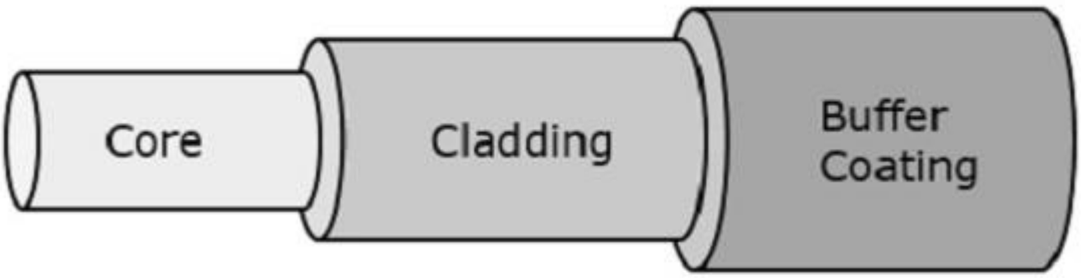
Where ${}_r\mu_d$ = refractive index of denser medium with respect to rarer medium. In most of the problems the rarer medium is chosen to be air with refractive index 1.

What Is an Optical Fibre?

Optical fibre is the technology associated with data transmission using light pulses travelling along with a long fibre which is usually made of plastic or glass. Metal wires are preferred for transmission in optical fibre communication as signals travel with fewer damages. Optical fibres are also unaffected by electromagnetic interference. The fibre optical cable uses the application of total internal reflection of light. The fibres are designed such that they facilitate the propagation of light along with the optical fibre depending on the requirement of power and distance of transmission. Single-mode fibre is used for long-distance transmission, while multimode fibre is used for distances. The outer cladding of these fibres needs better protection than metal wires.

Parts of a Fiber

The most commonly used optical fiber is **single solid di-electric cylinder** of radius **a** and index of refraction n_1. The following figure explains the parts of an optical fiber.



Parts of an Optical fiber

This cylinder is known as the **Core** of the fiber. A solid di-electric material surrounds the core, which is called as **Cladding**. Cladding has a refractive index n_2 which is less than n_1.

Cladding helps in −

- Reducing scattering losses.
- Adds mechanical strength to the fiber.

- Protects the core from absorbing unwanted surface contaminants.

Types of Optical Fibres

The types of optical fibres depend on the [refractive index](), materials used, and mode of propagation of light.

The classification based on the refractive index is as follows:

- **Step Index Fibres:** It consists of a core surrounded by the cladding, which has a single uniform index of refraction.
- **Graded Index Fibres:** The refractive index of the optical fibre decreases as the radial distance from the fibre axis increases.

The classification based on the materials used is as follows:

- **Plastic Optical Fibres:** The polymethylmethacrylate is used as a core material for the transmission of light.
- **Glass Fibres:** It consists of extremely fine glass fibres.

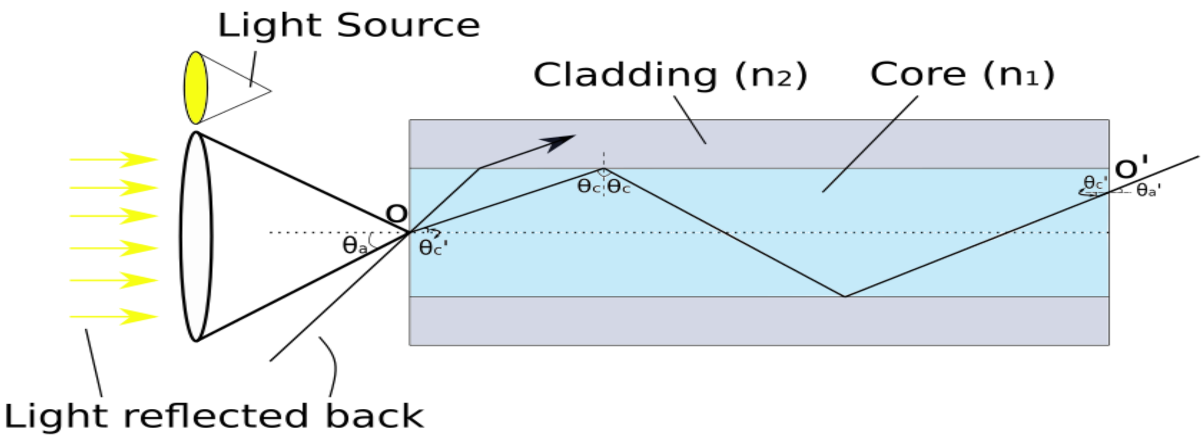
The classification based on the mode of propagation of light is as follows:

- **Single-Mode Fibres:** These fibres are used for long-distance transmission of signals.
- **Multimode Fibres:** These fibres are used for short-distance transmission of signals.

The mode of propagation and refractive index of the core is used to form four combination types of optic fibres as follows:

- Step index-single mode fibres
- Graded index-Single mode fibres
- Step index-Multimode fibres
- Graded index-Multimode fibres

How Does an Optical Fibre Work?



The optical fibre works on the principle of total internal reflection. Light rays can be used to transmit a huge amount of data, but there is a problem here – the light rays travel in straight lines. So unless we have a long straight wire without any bends at all, harnessing this advantage will be very tedious. Instead, the optical cables are designed such that they bend all the light rays inwards (using TIR). Light rays travel continuously, bouncing off the optical fibre walls and transmitting end to end data. Although light signals degrade over progressing distances, depending on the purity of the material used, the loss is much less than using metal cables. A Fibre Optic Relay System consists of the following components:

The Transmitter – It produces the light signals and encodes them to fit to transmit.

The Optical Fibre – The medium for transmitting the light pulse (signal).

The Optical Receiver – It receives the transmitted light pulse (signal) and decodes them to be fit to use.

The Optical Regenerator – Necessary for long-distance data transmission.

Functional Advantages

The functional advantages of optical fibers are −

- The transmission bandwidth of the fiber optic cables is higher than the metal cables.
- The amount of data transmission is higher in fiber optic cables.
- The power loss is very low and hence helpful in long-distance transmissions.
- Fiber optic cables provide high security and cannot be tapped.
- Fiber optic cables are the most secure way for data transmission.
- Fiber optic cables are immune to electromagnetic interference.
- These are not affected by electrical noise.

Physical Advantages

The physical advantages of fiber optic cables are −

- The capacity of these cables is much higher than copper wire cables.
- Though the capacity is higher, the size of the cable doesn’t increase like it does in copper wire cabling system.
- The space occupied by these cables is much less.
- The weight of these FOC cables is much lighter than the copper ones.
- Since these cables are di-electric, no spark hazards are present.
- These cables are more corrosion resistant than copper cables, as they are bent easily and are flexible.
- The raw material for the manufacture of fiber optic cables is glass, which is cheaper than copper.
- Fiber optic cables last longer than copper cables.

Disadvantages

Although fiber optics offer many advantages, they have the following drawbacks −

- Though fiber optic cables last longer, the installation cost is high.
- The number of repeaters are to be increased with distance.
- They are fragile if not enclosed in a plastic sheath. Hence, more protection is needed than copper ones.

Applications of Fiber Optics

The optical fibers have many applications. Some of them are as follows −

- Used in telephone systems
- Used in sub-marine cable networks
- Used in data link for computer networks, CATV Systems
- Used in CCTV surveillance cameras
- Used for connecting fire, police, and other emergency services.
- Used in hospitals, schools, and traffic management systems.
- They have many industrial uses and also used for in heavy duty constructions.

Example 1: The absolute refractive indices of glass and water are 4/3 and 3/2 respectively. If the speed of light in glass is 2×10^8 m/s, calculate the speed of light in (i) vacuum and (ii) water.

Solution: Refractive index of glass, $\mu_g = \frac{4}{3}$

∴ $$\mu_g = \frac{Speed\ of\ light\ in\ vaccum}{Speed\ of\ light\ in\ glass}$$

or $$\frac{4}{3} = \frac{Speed\ of\ light\ in\ vaccum}{2\times10^8}$$

Thus, speed of light in vacuum = $\frac{4\times2\times10^8}{3} = 2.67 \times 10^8\ m/s$

Refractive index of water (given), $\mu_w = \frac{3}{2}$

But we know that $$\mu_w = \frac{Speed\ of\ light\ in\ vaccum}{Speed\ of\ light\ in\ water}$$

∴ $$\frac{3}{2} = \frac{2.6\times10^8}{Speed\ of\ light\ in\ water}$$

Therefore, speed of light in water = 1.73×10^8 m/s

Example 2: Refractive index of water with respect to air is 4/3 and glass is 3/2. What is the refractive index of glass with respect to water?

Solution: For three media air, water and glass, we have

$$ {}^{a}\mu_{\mathrm{w}} \times {}^{\mathrm{w}}\mu_{\mathrm{g}} \times {}^{\mathrm{g}}\mu_{a} = 1 $$

$\therefore$

$$ {}^{\mathrm{w}}\mu_{\mathrm{g}} = \frac{1}{{}^{g}\mu_{a} \times {}^{a}\mu_{\mathrm{w}}} = \frac{{}^{a}\mu_{g}}{{}^{a}\mu_{\mathrm{w}}} = \frac{3/2}{4/3} = \frac{9}{8} $$

Thus, refractive index of glass with respect to water is 9/8.

Example 3: If the angle of incidence (i) for a light ray in air be 45^{0} and the angle of refraction (r) in glass be 30^{0}. Find refractive index of glass.

Solution: Refractive index of glass, $n = \frac{\sin 45^0}{\sin 30^0} = \frac{1}{\sqrt{2}} \times 2 = \sqrt{2}$

Self Assessment Question (SAQ)

1. What is total internal reflection?
2. What is critical angle for a medium of refractive index $\sqrt{2}$?
3. Using Fermat principle, establish condition of total internal reflection.

comes out to be positive, which

1.8 GLOSSARY

Beam – group of rays
Extreme – maximum or minimum
Angle of Incidence – angle between a beam striking a surface and the normal to surface **Angle of Reflection** – angle formed between the normal to a surface and reflected ray **Angle of Refraction** – angle formed between a refracted ray and the normal to the surface
Homogeneous – of the same kind, alike
Iterative – Frequentative

1.9 REFERENCES

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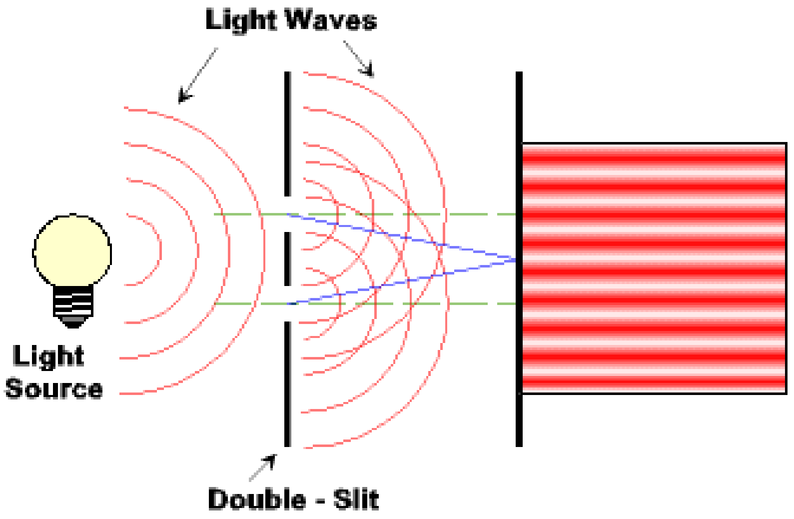
Interference of Light

In physics, **interference** is a phenomenon in which two waves superpose to form a resultant wave of greater or lower amplitude. Interference usually refers to the interaction of waves that are correlated or coherent with each other, either because they come from the same source or because they have the same or nearly the same frequency. Interference effects can be observed with all types of waves, for example, light, radio, acoustic, surface water waves or matter waves.



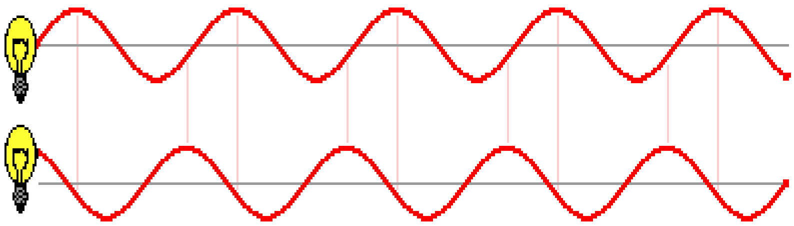
Conditions of Interference

When waves come together they can interfere constructively or destructively. To set up a stable and clear interference pattern, two conditions must be met:

1. The sources of the waves must be coherent, which means they emit identical waves with a constant phase difference.
2. The waves should be monochromatic - they should be of a single wavelength.

Coherent Sources

Those sources of light which emit light waves continuously of same wavelength, and time period, frequency and amplitude and have zero phase difference or constant phase difference are coherent sources.



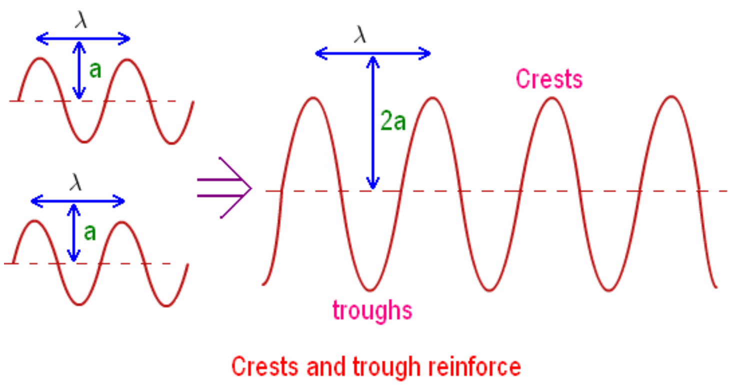
These two waves are coherent - they have a phase difference which is constant over time.

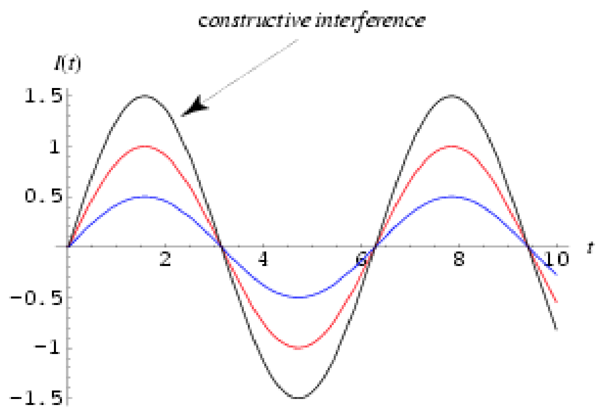
There are two types of interference.

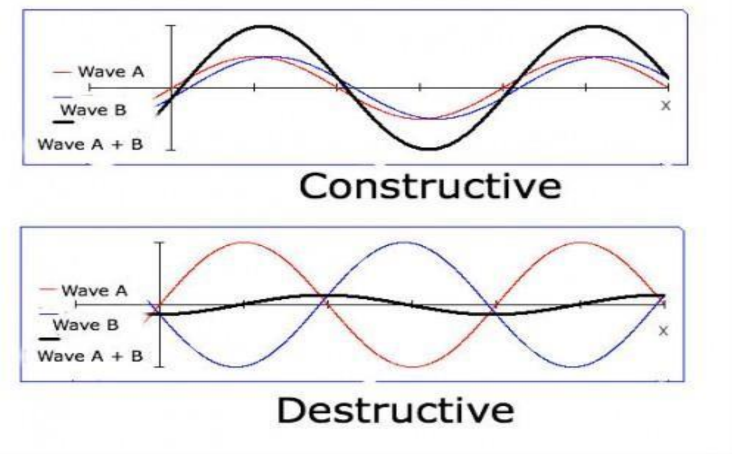
1. Constructive Interference
2. Destructive Interference

Constructive Interference

When two light waves superpose with each other in such a way that the crest of one wave falls on the crest of the second wave, and trough of one wave falls on the trough of the second wave, then the resultant wave has larger amplitude and it is called constructive interference.

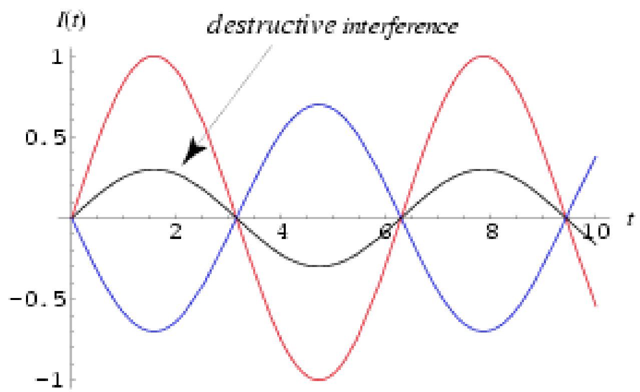


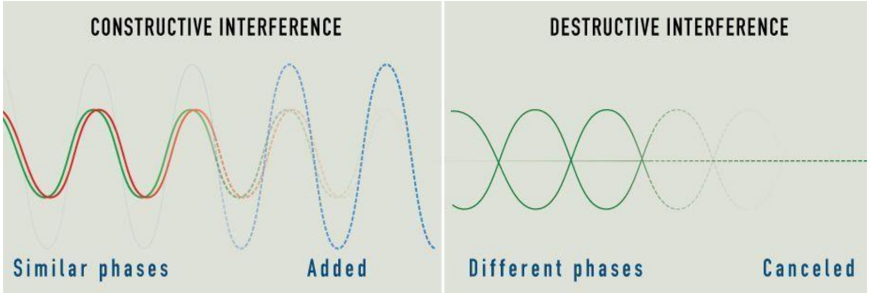




Destructive Interference

When two light waves superpose with each other in such a way that the crest of one wave coincides the trough of the second wave, then the amplitude of resultant wave becomes zero and it is called destructive interference.





Young's Double Slit Experiment

In 1801, an English physicist named Thomas Young performed an experiment that strongly inferred the wave-like nature of light.

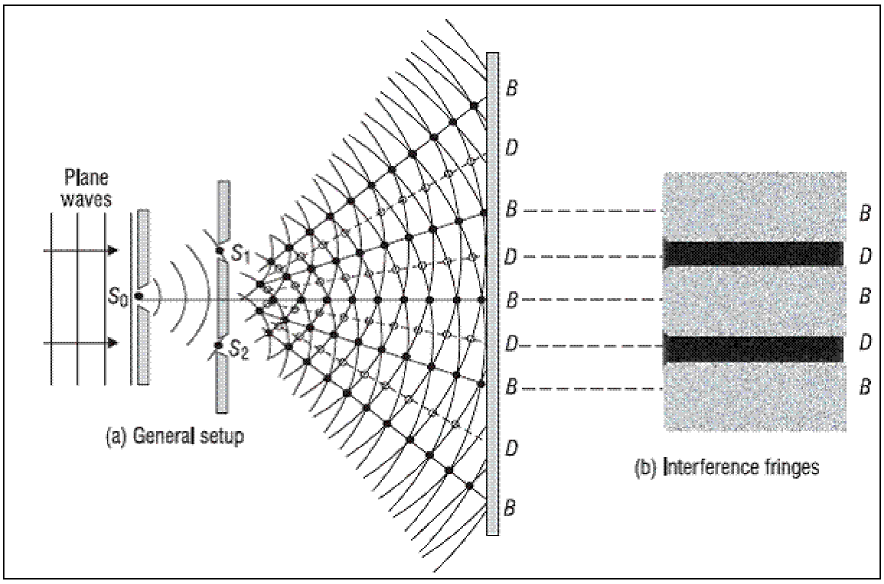


Fig: Young's double slit experiment

Thomas Young demonstrated the experiment on the interference of light. He allowed, light to fall on a pinhole S_0 and then at some distance away on two pinholes S_1 and S_2. S_1 and S_2 are equidistant from S_0 and are close to each other. Spherical waves spread out from S_0. Spherical waves also spread out from S_1 and S_2. These waves are of the same amplitude and wavelength. On the screen interference bands are produced which are alternatively dark and bright. The points such as B are bright because the crest due to the one wave coincides with the rest due to the other and therefore they reinforce with each other. The points such as D are dark because of the crest of one falls to on the trough of the other and they neutralize the effect of each other. Points, similar to B, where the trough of one falls on the trough of the other, are also bright because the two waves reinforce.

It is not possible to show interference due to two independent sources of light, because a large number of difficulties are involved. The two sources may emit light waves of largely different amplitude and wave length and the phase difference between the two may change with time.

Theory of Interference Fringes

Consider, a narrow monochromatic source S and two pinholes S_1 and S_2, equidistant from S. $S_1$and S_2 acts as two coherent sources separated by a distance d.

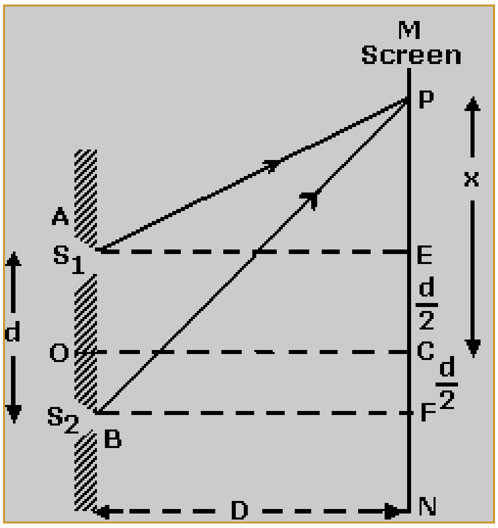


Fig: Young's double slit experiment

Let a screen be placed at a distance D from the coherent source. The point C on the screen is equidistant from S_1 and S_2. Therefore, the path difference between the two waves is zero. Thus, the point C has maximum intensity.

Consider a point P at a distance x from C. The waves reach at the point P from A and B.

Here,

$PE = x - \frac{d}{2}$

$PF = x + \frac{d}{2}$

Now from the triangle PAE we get,

$(AP)^2 = D^2 + (x - \frac{d}{2})^2$ ----------------------- (1)

Similarly, from the triangle PBF we get

$(BP)^2 = D^2 + (x + \frac{d}{2})^2$ --------------------- (2)

Subtracting equation (1) from equation (2)

$(BP)^2 - (AP)^2 = [D^2 + (x + \frac{d}{2})^2] - [D^2 + (x - \frac{d}{2})^2]$

or, $(BP)^2 - (AP)^2 = D^2 + x^2 + xd + \frac{d^2}{4} - D^2 - x^2 + xd - \frac{d^2}{4}$

or, $(BP)^2 - (AP)^2 = 2xd$

$\text{or}, (BP - AP)(BP + AP) = 2xd$

$\text{or}, (BP - AP) = 2xd/(BP + AP)$-------------------------(3)

As, $d \ll D$. So, we can assume that $BP \approx AP \approx D$. So, from equation (3) we can write-

$(BP - AP) = 2xd/(D + D)$

$\text{or}, (BP - AP) = 2xd/(D + D)$

$\therefore (BP - AP) = xd/D$

But $(BP - AP)$ is the path difference of the light at point P.

$\therefore$ The path difference $= xd/D$---------------------------- (4)

Again, we know, the phase difference $= \frac{2\pi}{\lambda} \times$ the path difference.

So, the phase difference of the light at point P $= \frac{2\pi}{\lambda} \times \frac{xd}{D}$------------------------ (5)

Condition for bright fringes:

If the path difference is a whole number multiple of wavelength λ, then the points will be bright.

i.e., $\frac{xd}{D} = n\lambda$ Where n = 0, 1, 2, 3……………..

$\therefore x = \frac{n\lambda D}{d}$----------------------(6)

This equation gives the distances of the bright fringes from the point C. At C, the path difference is zero and a bright fringe is formed.

When $n = 0,\ x_0 = 0$

$n = 1,\ x_1 = \frac{\lambda D}{d}$

$n = 2,\ x_2 = \frac{2\lambda D}{d}$

$n = 3,\ x_3 = \frac{3\lambda D}{d}$

……………………………

$n = n,\ x_n = \frac{n\lambda D}{d}$

Therefore, the distance between any two consecutive bright fringes

$x_2 - x_1 = \frac{2\lambda D}{d} - \frac{\lambda D}{d} = \frac{\lambda D}{d}$ -------------------------(7)

Condition for dark fringes:

If the path difference is an odd number multiple of half wavelength, then the point will be dark.

i.e., $\frac{x\,d}{D} = \frac{2n+1}{2}\lambda$

$\therefore\ x = \frac{(2n+1)\lambda D}{2d}$

This equation gives the distances of the dark fringes from the point C.

When, $n = 0,\ \ x_0 = \frac{\lambda D}{2\,d}$

$n = 1,\ x_1 = \frac{3\,\lambda D}{2\,d}$

$n = 2,\ x_2 = \frac{5\lambda D}{2d}$

$n = 3,\ x_3 = \frac{7\,\lambda\,D}{2\,d}$

………………………………

$n = n,\ \ x_n = \frac{(2n+1)\,\lambda\,D}{2d}$

The distance between any two consecutive dark fringes,

$x_2 - x_1 = \frac{5\lambda D}{2d} - \frac{3\lambda D}{2d} = \frac{\lambda D}{d}$ ---------------------------(8)

The distance between any two-consecutive bright or dark fringes is known as fringe width.

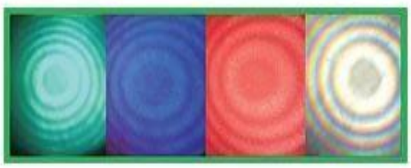
Therefore, alternately bright and dark parallel fringes are formed. The fringes are formed on both sides of C. Moreover, from equations (7) and (8), it is clear that the width of the bright fringe is equal to the width of the dark fringe. All the fringes are equal in width and are independent of the order of the fringe. The breadth of a bright or a dark fringe is, however, equal to half the fringe width and is equal to $\frac{\lambda D}{2d}$.

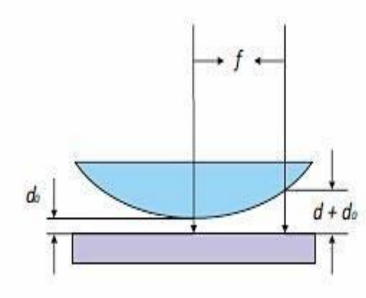
The fringe width $= \frac{\lambda D}{d}$

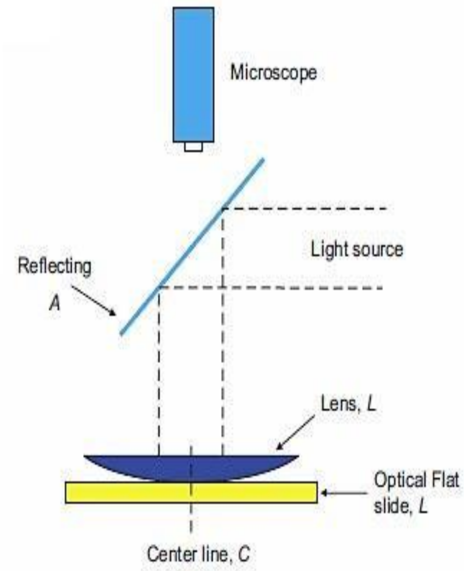
Therefore, (i) the width of the fringe is directly proportional to the wavelength of light, a λ. (ii) The width of the fringe is directly proportional to the distance between the two sources, a $\frac{1}{d}$. Thus, the width of the fringe increases (a) with increase in wavelength (b) with increase in the distance D and (c) by bringing the two sources A and B close to each other.

Newton's Ring

Newton's ring is a phenomenon in which an interference pattern is created by the reflection of light between two surfaces—a spherical surface and an adjacent flat surface. It is named after Isaac Newton, who first studied them in 1717.

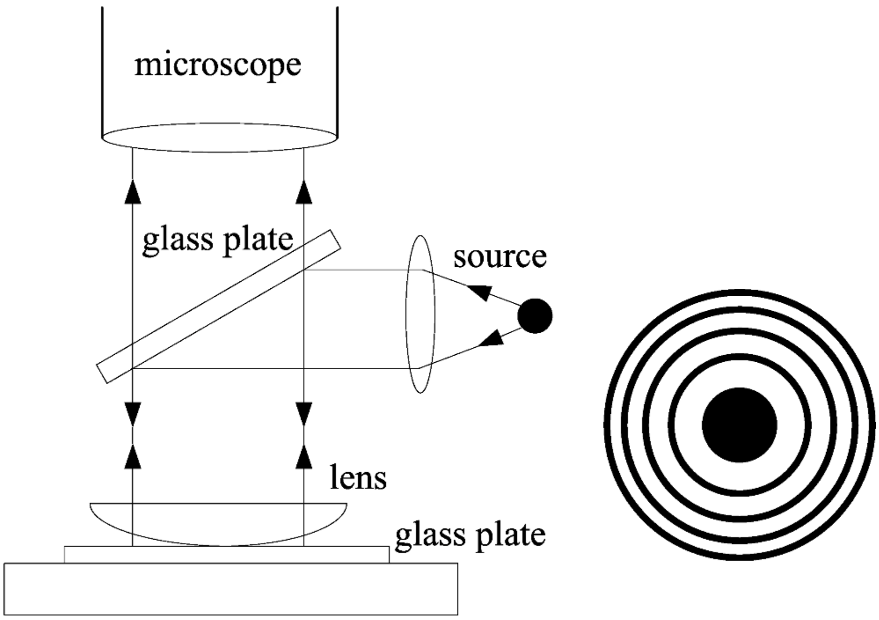






Newton's Ring Experiment

When a Plano-convex lens of long focal length is placed on a plane glass plate, a thin film of air is enclosed between the lower surface of the lens and the upper surface of the plate.



(a) (b)

The thickness of the air film is very small at the point of contact and gradually increases from the center outwards. The fringes produced with monochromatic light are circular. The fringes are concentric circles, uniform in thickness and with the point of contact as the center. When viewed with white light, the fringes are colored. With monochromatic light, bright and dark circular fringes are produced in the air film.

Determination of the Wavelength of Sodium Light using Newton's Ring

The arrangement used is shown in the figure below. S is a source of sodium light. A parallel beam of light from lens L_1 is reflected by the glass plate G inclined at an angle of 45^0 to the horizontal. L is a plano-convex lens of large focal length. Newton's rings are viewed through G by the travelling microscope M focused on the air film. Circular bright and dark rings are seen with the center dark. With the help of travelling microscope, the diameter of the n^{th} ring can be measured.

Fig.: Newton's ring experiment

The optical path difference between the rays is given by

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

Since, $\mu = 1$ for air and the incident angle $r = 0°$ therefore $\cos(r) = 1$ for normal incidence of light, so from equation (1) we can write-

$$\Delta = 2t - \frac{\lambda}{2} \quad \text{-------------------------(2)}$$

Let R be the radius of curvature of the lens. Let a dark fringe be located at distance r from the middle point of the lens and the thickness of the air film at r distance be t. By the Pythagorus theorem,

$$R^2 = r^2 + (R - t)^2$$

$$\text{or, } R^2 = r^2 + R^2 - 2Rt + t^2$$

$$\therefore \; r^2 = 2Rt - t^2 \quad \text{...(3)}$$

As $R \gg t$, so $2Rt \gg t^2$. So, equation (3) can be written as

$$r^2 = 2Rt \quad \text{...(4)}$$

Dark ring occurs when the optical path difference is

$$\Delta = \frac{(2m+1)\lambda}{2} \qquad \text{where, } m=0,1,2,3 \ldots\ldots\ldots$$

$$\text{or, } 2t - \frac{\lambda}{2} = \frac{(2m+1)\lambda}{2}$$

$$\therefore \; 2t = m\lambda \quad \text{...(5)}$$

where m=1,2,3, 4, ………..

substituting the value of equation (5) into equation (4), we get-

$r^2 = mR\lambda$

As here r is the radius of the m^{th} ring. So, it can be denoted by r_m.

$r_m^2 = mR\lambda$ ……………………………………………………(6)

Suppose, the diameter of the m^{th} ring = D_m.

But, $r_m = \frac{D_m}{2}$

$\frac{D_m^2}{4} = mR\lambda$

$D_m^2 = 4mR\lambda$ ……………………………………………………(7)

Let the diameter of the $(m + n)$th dark ring be D_{n+m}. Similarly, we can write

$D_{m+n}^2 = 4(m + n)R\lambda$ ------------------------------- (8)

Subtracting equation from number (7) from (8)

$D_{n+m}^2 - D_n^2 = 4\,(n+m)\,\lambda\,R - 4\,m\,\lambda\,R$

$\lambda = \frac{D_{n+m}^2 - D_n^2}{4nR}$

Hence, λ can be calculated.

Suppose, the diameter of the 5 th ring and the 15 th ring are determined. Then, n = 15 – 5 = 10

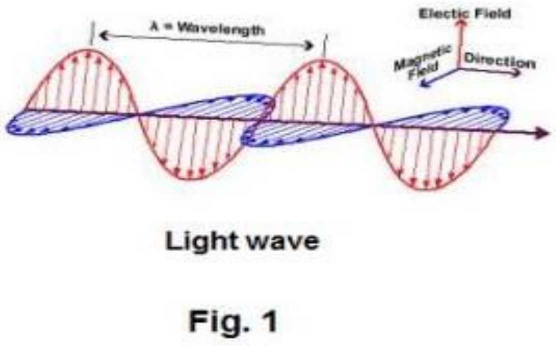
$\lambda = \frac{D_{15}^2 - D_5^2}{4\times10\times R}$

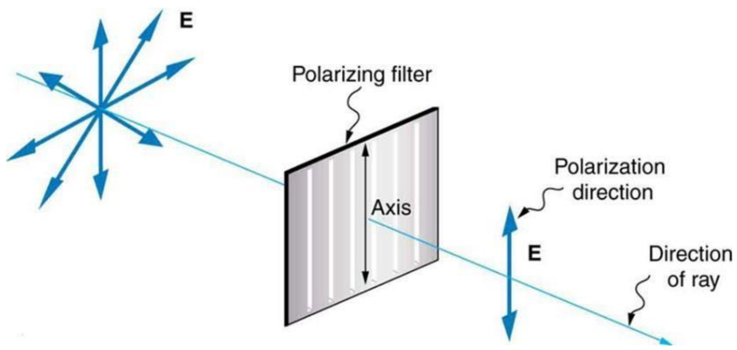
The radius of curvature of the lower surface of the lens is determined with the help of spherometer but more accurately it is determined by Boy's method. Hence the wavelength of a given monochromatic source of light can be determined.

Polarization

The process by which light waves vibrating in different planes can be made to vibrate in a particular plane is called polarization of light. Sound waves in a gas or liquid do not exhibit polarization, since the oscillation is always in the direction the wave travels.

In an electromagnetic wave, both the electric field and magnetic field are oscillating but in different directions.

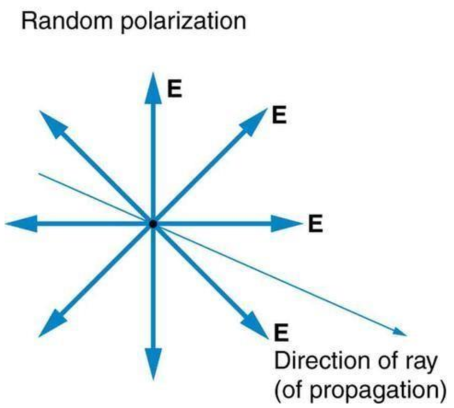




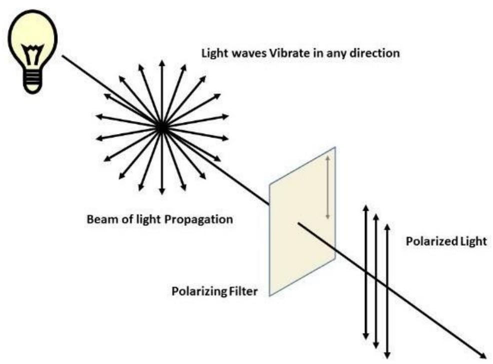
Electromagnetic Waves

Some terms relating to polarization

(1) Unpolarized light: Ordinary light waves whose vibrations normal to the direction of propagation, spread all around the source with equal amplitude is called unpolarized light. The figure given below shows the unpolarized light.

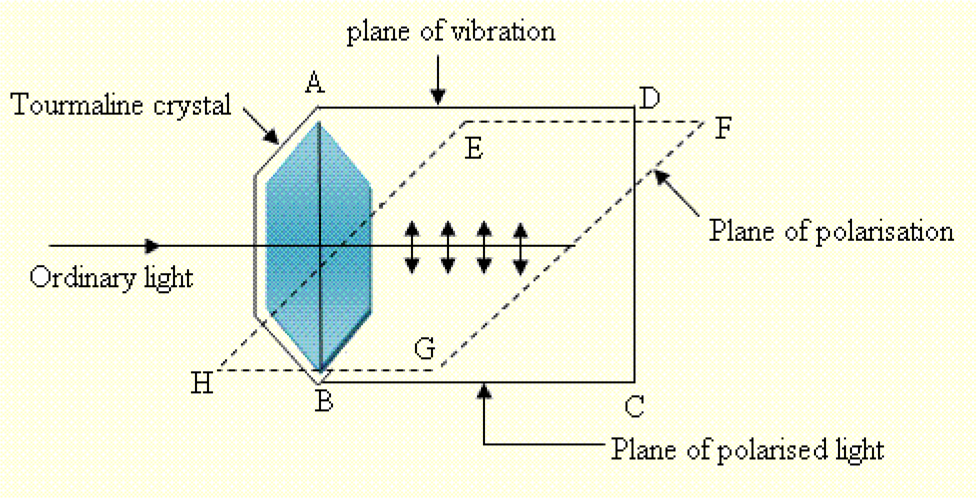


(2) Polarized light: The transverse light waves vibrating on a particular plane or parallel to it is called polarized light.



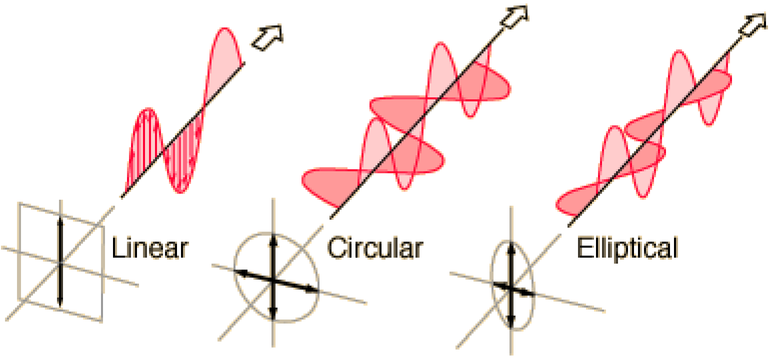
(3) **Plane of vibration:** The plane in which the particles of the light waves vibrate is called the plane of vibration. The below figure shows the plane of vibration. ABCD is the plane of vibration.

(4) **Plane of polarization:** The plane which exists normal to the plane of vibration is called the plane of polarization. In the figure EFGH is the plane of polarization.



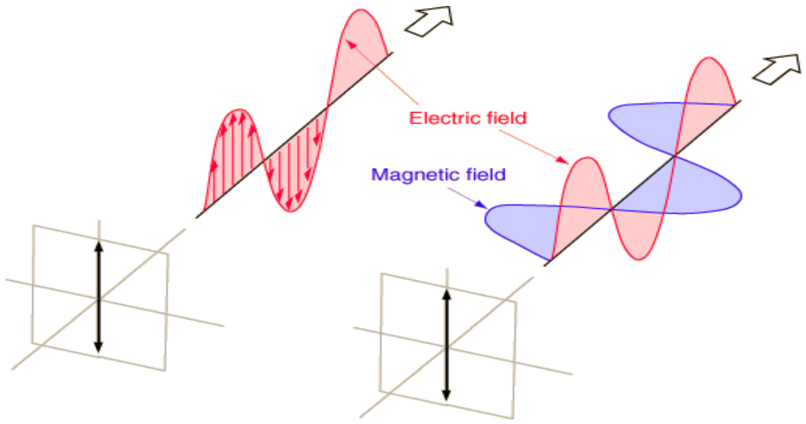
Classification of Polarization

Light in the form of a plane wave in space is said to be linearly polarized. Light is a transverse electromagnetic wave, but natural light is generally unpolarized, all planes of propagation being equally probable. If light is composed of two plane waves of equal amplitude by differing in phase by 90°, then the light is said to be circularly polarized. If two plane waves of differing amplitude are related in phase by 90°, or if the relative phase is other than 90° then the light is said to be elliptically polarized.



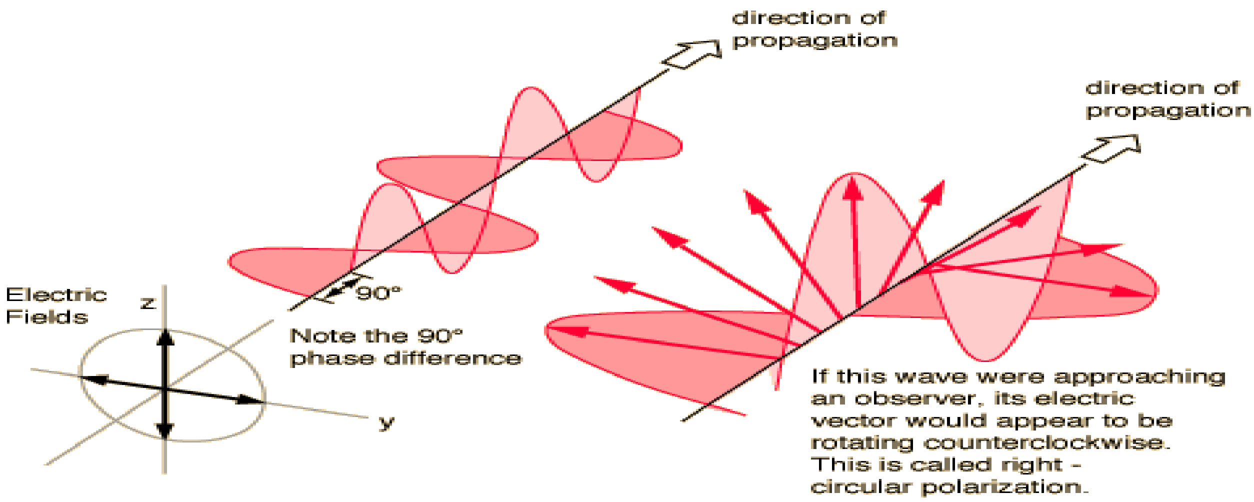
Linear Polarization

A plane electromagnetic wave is said to be linearly polarized. The transverse electric field wave is accompanied by a magnetic field wave as illustrated.



Circular Polarization

Circularly polarized light consists of two perpendicular electromagnetic plane waves of equal amplitude and 90° difference in phase. The light illustrated is right- circularly polarized.



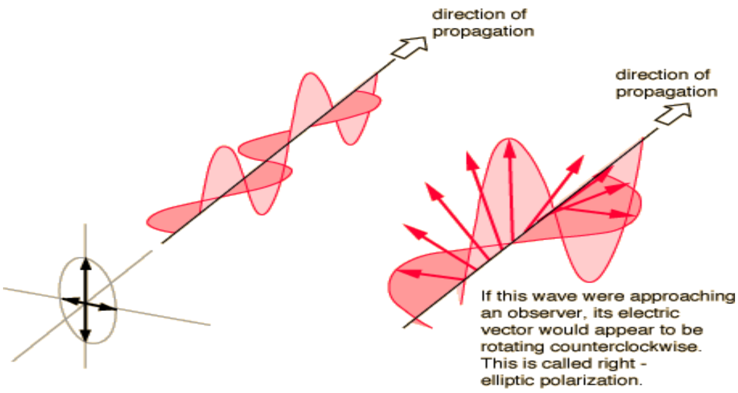
If light is composed of two plane waves of equal amplitude but differing in phase by 90°, then the light is said to be circularly polarized. If you could see the tip of the electric field vector, it would appear to be moving in a circle as it approached you.

If while looking at the source, the electric vector of the light coming toward you appears to be rotating counterclockwise, the light is said to be right-circularly polarized. If clockwise, then left-circularly polarized light. The electric field vector makes one complete revolution as the light advances one wavelength toward you. Another way of saying it is that if the thumb of your right hand were pointing in the direction of propagation of the light, the electric vector would be rotating in the direction of your fingers.

Circularly polarized light may be produced by passing linearly polarized light through a quarter-wave plate at an angle of 45° to the optic axis of the plate.

Elliptical Polarization

Elliptically polarized light consists of two perpendicular waves of unequal amplitude which differ in phase by 90°. The illustration shows right- elliptically polarized light.



Production of linearly polarized light

Linearly polarized light may be produced from unpolarized light using of the following five optical phenomena:

1. Reflection
2. Refraction
3. Scattering
4. Selective absorption (dichroism) and
5. Double refraction

Brewster's Law

In 1811 Brewster's proposed it. The law states that the tangent of the angle at which polarization is obtained by reflection is numerically equal to the refractive index of the medium.

If θ_p is the angle and μ is the refractive index of the medium, then

$$\mu = \tan\theta_p$$

This is known as Brewster's law.

Mathematical derivation:

If natural light is incident on a smooth surface at the polarizing angle, it is reflected along PC and refracted along PB, as shown in figure. Brewster found that the maximum polarization of reflected ray occurs when it is at right angle to the refracted ray.

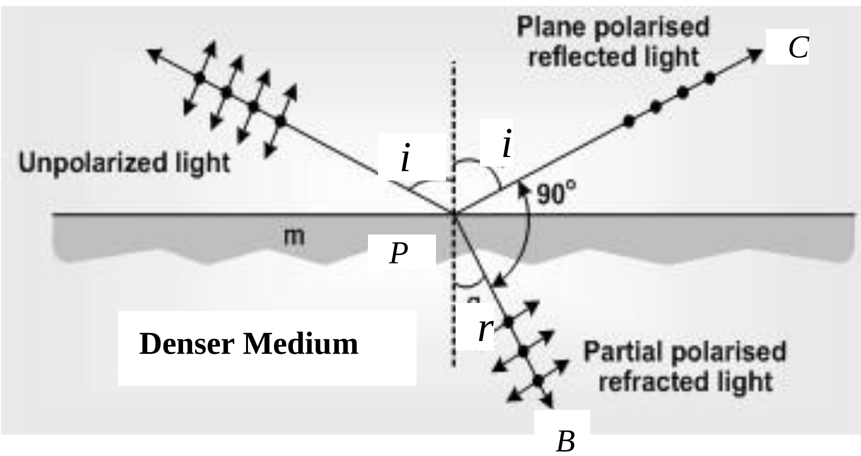


Fig.: Production of plane polarized light by the method of reflection.

It means that

$i + r = 90°$

$\therefore r = 90° - i$ ....(1)

Where, i and r represents the incident angle and the refractive angle respectively.

According the Snell's law,

$\frac{\sin i}{\sin r} = \frac{\mu_2}{\mu_1}$ ------------------------(2)

Where μ_2 and μ_1 are the absolute refractive index of the reflecting surface and the surrounding medium.

It follows from equation (1) and (2) that

$$\frac{\sin i}{\sin(90° - i)} = \frac{\mu_2}{\mu_1}$$

$$\text{or,} \frac{\sin i}{\cos i} = \frac{\mu_2}{\mu_1}$$

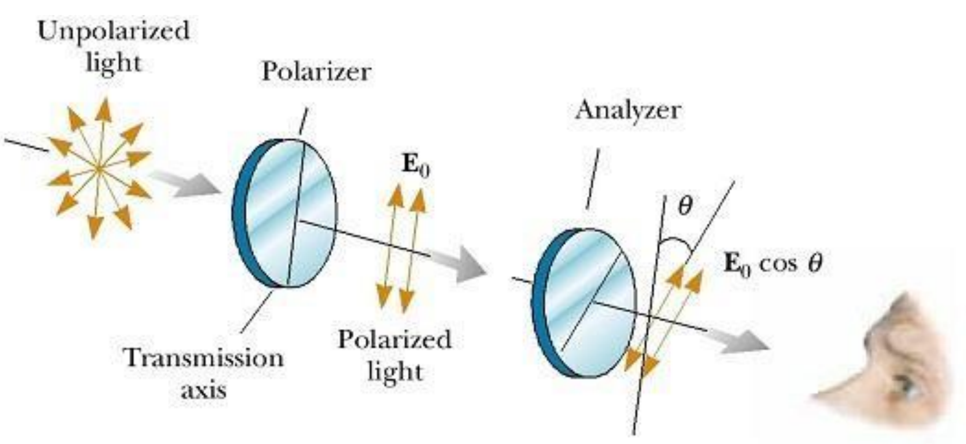
$\therefore \tan i = \frac{\mu_2}{\mu_1}$ ....(3)

Equation (3) shows that the polarizing angle depends on the refractive index of the reflecting surface. The polarizing angle i is also known as Brewster angle and denote as θ_B. Light reflected from any angle other than Brewster angle is partially polarized.

Specific rotation:

The specific rotation for a given wavelength of light at a given temperature is defined conventionally as the rotation produced by one decimeter long column of the solution containing 1 gm of optically active material per c.c. of solution. It is denoted by S.

$$[S]_{\lambda}^{t} = \frac{\theta}{l \times C} = \frac{Rotation\ in\ degrees}{length\ in\ decimeters\ \times conc.\ in\ \frac{gm}{c.c.}} = \frac{10\theta}{l(cm)C}$$



Malues Law:

According to malus, when completely plane polarized light is incident on the analyzer, the intensity I of the light transmitted by the analyzer is directly proportional to the square of the cosine of angle between the transmission axes of the analyzer and the polarizer.

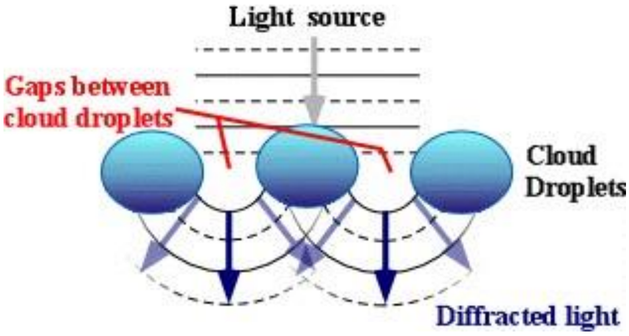
If E_1 is the intensity of the transmitted wave and θ is the angle between the planes of polarizer and the analyser. Then,

E_1 a $cos^2\,\theta$

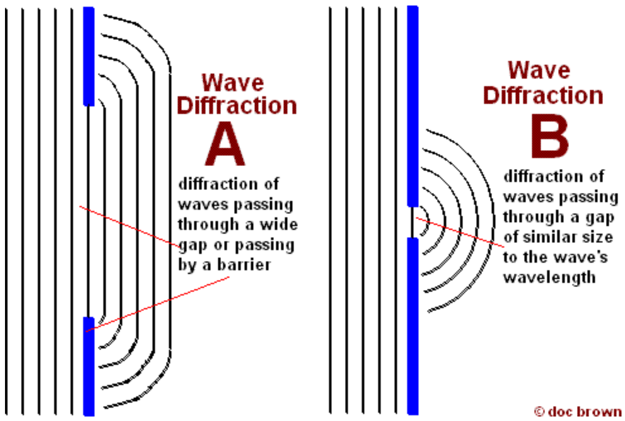
$E_1 = E\,cos^2$; Where E is the intensity of the incident polarized light.This

is known as Malues law of polarization.

Diffraction is the slight bending of light as it passes around the edge of an object. The amount of bending depends on the relative size of the wavelength of light to the size of the opening. If the opening is much larger than the light's wavelength, the bending will be almost unnoticeable. However, if the two are closer in size or equal, the amount of bending is considerable, and easily seen with the open eye.



In the atmosphere, diffracted light is actually bent around atmospheric particles -- most commonly, the atmospheric particles are tiny water droplets found in clouds. Diffracted light can produce fringes of light, dark or colored bands. An optical effect that results from the diffraction of light is the silver lining sometimes found around the edges of clouds or coronas surrounding the sun or moon. The illustration above shows how light (from either the sun or the moon) is bent around small droplets in the cloud.



Condition of diffraction

There are two conditions for the production of diffraction

(1) In case of straight edge: The edge should be very sharp and its width is to be equal to or is of the order of the wavelength, λ of light.

(2) In case of thin hole: the diameter of the hole should be extremely very small such that it is equal to or is of the order of the wavelength λ of light.

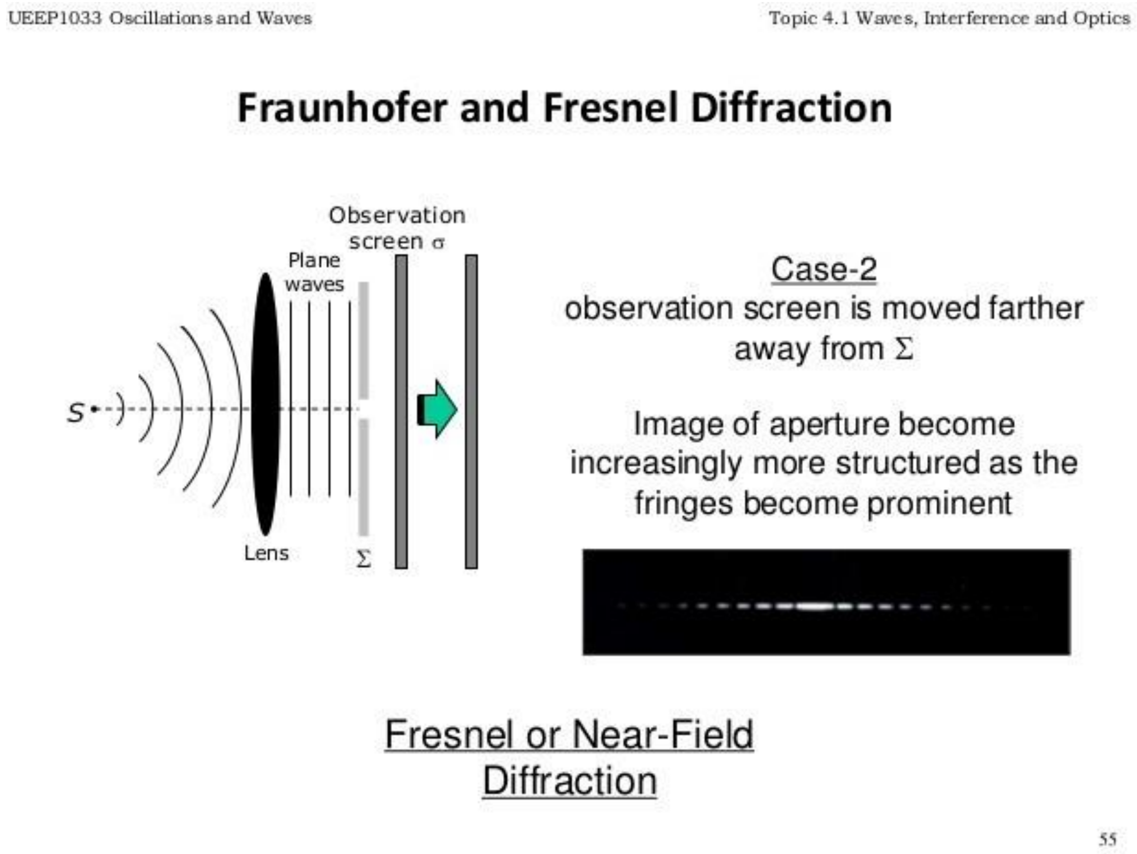
Diffraction is of two types

(1) Fresnel's class of diffraction
(2) Fraunhofer's class of diffraction

Fresnel's class of diffraction

When the source of light and the screen are at finite distance from the inside obstacle, then the diffraction observed due to the obstacle is called the Fresnel class of diffraction.

In this type of diffraction wave fronts are generally spherical or cylindrical. This type of diffraction occurs in a straight edge, fine wire and narrow slit.



Fraunhofer's class of diffraction

When the source of light and the screen are effectively at infinite distance from the obstacle or aperture causing diffraction, then that type of diffraction is called Fraunhofer's class of diffraction.

In this type of diffraction wave fronts incident on the obstacle or aperture is plane.