UNIT 7 WAVE OPTICS

Warm greetings:

Dear students already we learnt about ray optics. Now we are going to discuss about the following topics.

- Theories on light
- Huygens' Principle
- Proof for laws of refraction using Huygens' Principle
- Proof for laws of refraction using Huygens' Principle

THEORIES ON LIGHT:

- Light is a form of energy that is transferred from one place to another.
- A glance at the evolution of various theories of light put forth by scientists will give not only an over view of the nature of light but also its propagation and some phenomenon demonstrated by it.

Corpuscular theory:

- Sir Isaac Newton (1672) gave the corpuscular theory of light which was also suggested earlier by Descartes (1637)to explain the laws of reflection and refraction.
- According this theory, light is emitted as tiny, massless (negligibly small mass) and perfectly elastic particles called corpuscles.
- As the corpuscles are very small, the source of light does not suffer appreciable loss of mass even if it emits light for a long time.
- On account of high speed, they are unaffected by the force of gravity and their path is a straight line in a medium of uniform refractive index.
- The energy of light is the kinetic energy of these corpuscles.
- When these corpuscles impinge on the retina of the eye, the vision is produced. The different sizes of the corpuscles give different colours to light.
- When the corpuscles approach a surface between two media, they are either repelled (or) attracted.
- The reflection of light is due to the repulsion of the corpuscles by the medium and refraction of light is due to the attraction of the corpuscles by the medium.

- This theory could not explain the reason why the speed of light is lesser in denser medium than in rarer medium and also the phenomena like interference, diffraction and polarisation.

Wave theory:

- Christian Huygens (1678) proposed the wave theory to explain the propagation of light through a medium.
- According to him, light is a disturbance from a source travels that as longitudinal mechanical waves through the ether medium (that was presumed to pervade all space) as mechanical wave requires a medium for its propagation.
- The wave theory could successfully explain phenomena of reflection, refraction,interference and diffraction of light.
- Later, the existence of ether in all space was proved to be wrong.
- Hence, this theory could not explain the propagation of light through vacuum. The phenomenon of polarisation could not be explained by this theory as it is the property of only transverse waves.

Electromagnetic wavetheory:

- Maxwell (1864) proved that light is an electromagnetic wave which is transverse in nature carrying electromagnetic energy.
- He could also show that no medium is necessary for the propagation of electromagnetic waves.
- All the phenomenon of light could be successfully explained by this theory.
- Nevertheless, the interaction phenomenon of light with matter like photoelectric effect and Compton effect could not be explained by this theory.

Quantum theory:

- Albert Einstein (1905), endorsing the views of Max Plank (1900), was able to explain photoelectric effect in which light interacts with matter as *photons* to eject the electrons.
- A photon is a discrete packet of energy.
- Each photon has energy E of, $E = h\upsilon$

Where, h is Plank's constant ($h = 6.625 \times 10^{-34}$ Js) and

υ is frequency of electromagnetic wave.

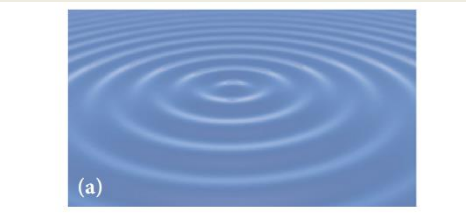
- As light has both wave as well as particle nature it is said to have dual nature. It is concluded that light propagates as a wave and interacts with matter as a particle.

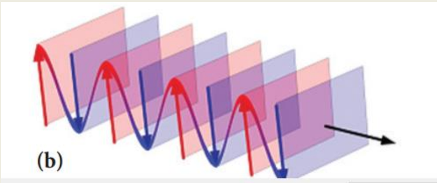
WAVE NATURE OF LIGHT:

- Light is a transverse, electromagnetic wave.
- The wave nature of light was first demonstrated through experiments like interference and diffraction.
- The transverse nature of light is demonstrated in polarization.
- Like all electromagnetic waves, light can travel through vacuum.

Wave optics:

- Wave optics deals with the wave characteristics of light. Even the law of reflection and refraction are proved only with the help of wave optics.
- Though light propagates as a wave, its direction of propagation is still represented as a ray.
- A good example for wave propagation is the spreading of circular ripples on the surface of still water from a point where a stone is dropped.
- The molecules (or) particles of water at a point are moving only up and down (oscillate) when a ripple passes through that point.
- All these particles on the circular ripple are in the same phase of vibration as they are all at the same distance from the center. The ripple represents a wavefront as shown in Figure 7.1(a).
- A *wavefront* is the locus of points which are in the same state (or) phase of vibration. When a wave propagates it is treated as the propagation of wavefront.
- The wavefront is always perpendicular to the direction of the propagation of the wave.
- As the direction of ray is in the direction of propagation of the wave, the wavefront is always perpendicular to the ray as shown in Figure 7.1(b)





The shape of a wavefront observed at a point depends on the shape of the source and also the distance at which the source is located. A point source located at a finite distance gives spherical wavefronts. An extended (or) line source at finite distance gives cylindrical wavefronts. Any source that is located at infinity gives plane wavefront as shown in Figure 7.2.

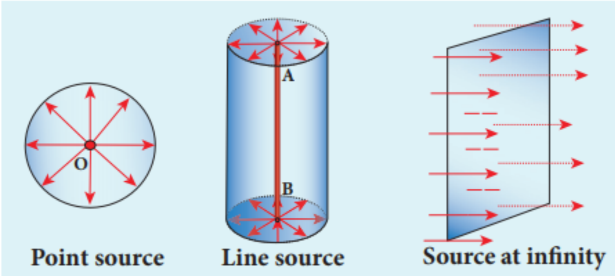


Figure 7.2 Wavefronts

Huygens' Principle:

- ✓ Huygens principle is basically a geometrical construction which gives the shape of the wavefront at any time if we know its shape at $t = 0$.
- ✓ According to Huygens principle, each point on the wavefront behaves as the source of secondary wavelets spreading out in all directions with the speed of the wave. These are called as secondary wavelets.
- ✓ The envelope to all these wavelets gives the position and shape of the new wavefront at a later time.
- ✓ Thus, Huygens' principle explains the propagation of a wavefront. The propagation of a spherical and plane wavefront can be explained using Huygens' principle.
- ✓ Let, *AB* be the wavefront at a time, $t = 0$.
- ✓ According to Huygens' principle, every point on *AB* acts as a source of secondary wavelet which travels with the speed of the wave (speed of light *c*). To find the position of the wavefront after a time *t*, circles of radius equal to *ct* are drawn with points *P*, *Q, R* ... etc., as centers on *AB*.
- ✓ The forward envelope (or) the tangent $A'B'$ of the small circles is the new wavefront at that instant *t*.
- ✓ The wavefront $A'B'$ will be a spherical wavefront from a point object which is at a finite distance as shown in Figure 7.3(a) and it is a plane wavefront if the source of light is at a large distance (infinity) as shown in Figure 7.3(b).

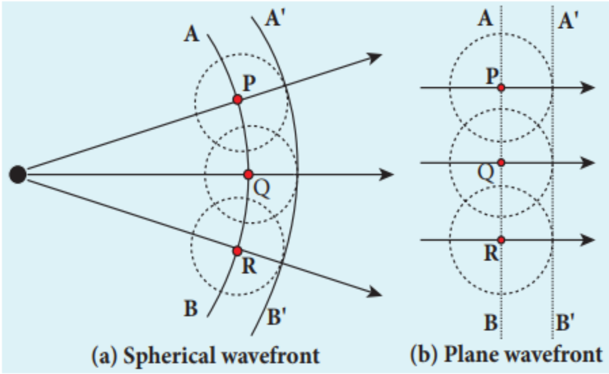


Figure 7.3 Huygens' Principle

- ✓ There is one shortcoming in the above Huygens' construction for propagation of a wavefront. It could not explain the absence of backward wave which also arises in the above construction.
- ✓ According to electromagnetic wave theory, the backward wave is ruled out inherently. However, Huygens' principle is a good diagrammatic construction which explains the propagation of the wavefront.

Proof for laws of reflection using Huygens' Principle:

Let us consider a parallel beam of light is incident on a reflecting plane surface such as a plane mirror *XY* as shown in Figure 7.4. The incident wavefront is *AB* and the reflected wavefront is *A′ B ′*.

These wavefronts are perpendicular to the incident rays *L*, *M* and reflected rays *L′* ,*M ′* respectively. By the time point *A* of the incident wavefront touches the reflecting surface, the point *B* is yet to travel a distance *BB′* to touch the reflecting surface at *B′* . When the point *B* touches the reflecting surface at *B′* , the point *A* would have reached *A′* .

This is applicable to all the points on the wavefront. Thus, the reflected wavefront *A′ B ′* emanates as a plane wavefront. The two normals *N* and *N′* are considered at the points where the rays *L* and *M* fall on the reflecting surface. As reflection happens in the same medium, the speed of light is same before and after

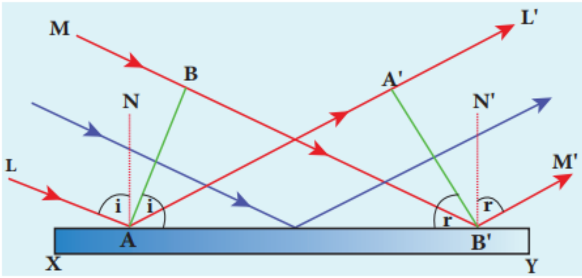


Figure 7.4 Laws of reflection

the reflection. The time taken for the light to travel from B to B' and A to A' are the same. Thus, the distance BB' is equal to the distance AA' ; $(AA' = BB')$.

(i) The incident rays, the reflected rays and the normal are in the same plane.

(ii) Angle of incidence,

$$\angle i = \angle NAL = 90^o - \angle NAB = \angle BAB'$$

(iii) Angle of reflection,

$$\angle r = \angle N'B'M' = 90^o - \angle N'B'A' = \angle A'B'A$$

For the two right angle triangles, $\Delta ABB'$ and $\Delta B'A'A$, the two right angles, $\angle B$ and $\angle A'$ are equal, ($\angle B$ and $\angle A' = 90^o$);

the two sides, AA' and BB' are equal, ($AA' = BB'$); the side AB' is common. Thus, the two triangles are congruent. As per the property of congruency, the two angles, $\angle BAB'$ and $\angle A'B'A$ must also be equal.

$$i = r$$

Hence, the laws of reflection are proved.

Proof for laws of refraction using Huygens' Principle:

Let us consider a parallel beam of light is incident on a refracting plane surface XY such as a glass as shown in Figure 7.5. The incident wavefront AB is in rarer medium (1) and the refracted wavefront $A'B'$ is in denser medium (2).

These wavefronts are perpendicular to the incident rays L, M and refracted rays L', M' respectively. By the time the point A of the incident wavefront touches the refracting surface, the point B is yet to travel a distance BB' to touch the refracting surface at B'.

When the point B touches the refracting surface at B', the point A would have reached A' in the other medium. This is applicable to all the points on the wavefront.

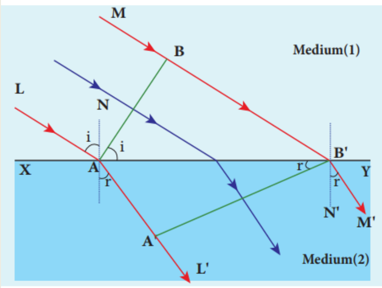


Figure 7.5 Law of refraction

Thus, the refracted wavefront *A 'B ''* emanates as a plane wavefront. The two normals *N* and *N'* are considered at the points where the rays *L* and *M* fall on the refracting surface.

As refraction happens from rarer medium (1) to denser medium (2), the speed of light is v_1 and v_2 before and after refraction and v_1 is greater than v_2, ($v_1 > v_2$). But, the time taken *t* for the ray to travel from *B* to *B'* is the same as the time taken for the ray to travel from *A* to *A'* .

$$t = \frac{BB'}{v_1} = \frac{AA'}{v_2} \text{ (or) } \frac{BB'}{AA'} = \frac{v_1}{v_2}$$

(i) The incident rays, the refracted rays and the normal are in the same plane.

(ii) Angle of incidence,

$$i = \angle NAL = 90^\circ - \angle NAB = \angle BAB'$$

Angle of refraction,

$$r = \angle N'B'M' = 90^\circ - \angle N'B'A' = \angle A'B'A$$

For the two right angle triangles $\Delta ABB'$ and $\Delta AA'B'$,

$$\frac{\sin i}{\sin r} = \frac{BB'/AB'}{AA'/AB'} = \frac{BB'}{AA'} = \frac{v_1}{v_2} = \frac{c/v_2}{c/v_1}$$

Here, *c* is speed of light in vacuum. The ratio *c*/*v* is a constant, called refractive index of the medium. The refractive index of medium (1) is, $c/v_1 = n_1$ and that of medium (2) is, $c/v_2 = n_2$.

In ratio form,

$$\frac{\sin i}{\sin r} = \frac{n_2}{n_1}$$

In product form,

$$n_1 \sin i = n_2 \sin r$$

Hence, the laws of refraction are proved. In the same way the laws of refraction can be proved for wavefront travelling from denser to rarer medium also. The speed of light is inversely proportional to the refractive index of the medium υ α 1/ n and also directly proportional to wavelength of light ($v \propto \lambda$) . Hence,

$$\frac{\lambda_1}{\lambda_2} = \frac{n_2}{n_1}$$

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