Class 12 – Wave Theory of Light (Q / A)

(Topics Covered : Wave theory of light, Huygens’ Principle, Wave-front & Wave-normal)

Q. 1. What are the different theories of the nature of light?
A. The different theories of nature of light from the 17th century to the modern times are –
   - Newton’s corpuscular theory
   - Huygens’ wave theory of light propagation
   - Maxwell’s electromagnetic theory
   - The photon model of the modern quantum theory by Planck and Einstein

Q. 2. What is the basis of Newton’s corpuscular theory of light? What are its assumptions?
A. Sir Isaac Newton championed the corpuscular theory of light which assumed that light consists of a stream of corpuscles emitted by a luminous source.

Postulates of the corpuscular theory:
1. Light corpuscles are minute, light and perfectly elastic particles.
2. A luminous source emits light corpuscles in all directions which then travel at high speed in straight lines in a given medium.
3. The constituent colours of white light are due to different sizes of the corpuscles.
4. The light corpuscles stimulate the sense of sight on their impact on the retina of the eye.
5. The reflective surface exerts a force of repulsion normal to the surface on the light corpuscles when they strike the surface.
6. A transparent denser medium exerts a force of attraction normal to the surface on the light corpuscles striking the surface. This force is different for different media.

A consequence of the assumption (6) is that, according to the corpuscular theory, the speed of light in any denser medium is greater than that in air and has different values for different mediums. It was known from the earliest recorded times that when sight is incident on the surface of glass or water, it is partly reflected and partly transmitted, simultaneously. To explain this, Newton postulated that the corpuscles must have fits of easy reflection and fits of easy transmission and must pass periodically from one state to the other.

Q. 3. What are the drawbacks of Newton’s corpuscular theory of light?
A. Newton’s corpuscular theory had the following drawbacks:
   1. The theory predicted that the speed of light in a denser medium should be greater than that in air. This was disproved when experiment showed that the velocity of light in water is less than that in air (carried out in 1850 by French physicist Jean Bernard Leon Foucault).
   2. The theory could not satisfactorily explain the phenomenon of polarization and the simultaneousness of reflection and refraction.
   3. The corpuscular theory failed to explain the phenomena of diffraction and interference.
4. There was no basis for the hypothesis that the constituent colours of white light are due to different sized corpuscles.

Q. 4. What was Maxwell’s concept of light?

A. James Clark Maxwell developed a mathematical theory on the intimate relationship between electricity and magnetism. His theory predicted light to be a high frequency transverse electromagnetic wave in ether. The speed of the electromagnetic waves in a medium, as calculated on the basis of Maxwell’s theory, was experimentally found to be equal to the measured speed of the light in that medium. Maxwell’s electromagnetic theory of light could account for all the known phenomena regarding the propagation or transmission of light through space and through matter.

Q. 5. What is the photon model or quantum hypothesis of light?

A. To explain the interaction of light and matter (as in emission or absorption of radiation), Max Planck (in 1900) and Einstein (in 1905) hypothesized light as concentrated or localized packets of energy. Such an energy packet is called a quantum of energy, which was given the name photon much later (in 1927 by Gilbert Lewis). For a radiation of frequency \( v \), a quantum of energy is \( hv \), where \( h \) is Planck’s constant.

‘Localization’ of energy in a region gives light its particle nature while frequency is a wave characteristic. The complementary properties of particle and wave of light quanta are reconciled as follows: light propagates as wave but interacts with matter as particle.


A. Huygens’ wave theory of light:

1. Light emitted by a source propagates in the form of waves. Huygens’ original theory assumed them to be longitudinal waves.
2. In a homogeneous isotropic medium, light from a point source spreads by spherical waves.
3. It was presumed that a wave motion needed a medium for its propagation. Hence, the theory postulated a medium called aluminiferous ether that exists everywhere, in vacuum as well as in transparent bodies. Ether had to be assigned some extraordinary properties, a high modulus of elasticity (to account for the high speed of light), zero density (so that it offers no resistance to planetary motions) and perfect transparency.
4. The different colours of light are due to the different wavelengths.

Merits:

1. Huygens’ theory satisfactorily explains reflection and refraction as well as their simultaneity.
2. In explaining refraction, the theory concludes that the speed of light in denser medium is less than that in a rarer medium, in agreement with experimental findings.
3. The theory was later used by Young, Fraunhoffer and Fresnel to satisfactorily explain interference, diffraction and rectilinear propagation of light. The phenomenon of polarization could also be explained considering the light waves to transverse.

Demerits:

1. It was found much later that the hypothetical medium, aluminiferous ether, has no experimental basis. Einstein discarded the idea of ether completely.
2. Phenomena like photoelectric effect, Compton Effect, etc. cannot be explained on the basis of the wave theory.

Q. 7. Define and explain the concept of wave-front and wave-normal.

A. Wave-Front: A wave-front is a surface of all neighbouring points which receive light waves from a source at the same instant and are in the same phase.

Explanation: Consider a point source of light $O$ in a homogeneous isotropic medium in which the speed of light is $v$. The source emits light in all directions. In time $t$, the disturbance (light energy) from the source covers a distance $vt$ in all directions, i.e., it reaches out to all points which are at a distance $vt$ from the point source. The locus of these points which are in the same phase is the surface of a sphere with the centre $O$ and radius $vt$. Such a spherical surface is called a spherical wave-front.

An extended linear source (such as an aperture in the form of a narrow slit) would give rise to cylindrical wave-fronts.

Wave-Normal: A wave-normal at a point on a wave-front is defined as a line drawn perpendicular to the wave-front in the direction of propagation of the wave-front.

Explanation: In a homogeneous isotropic medium, a wave-front moves parallel to itself. Thus, at any point in the medium, the direction in which the wave-front moves is always perpendicular to the wave-front itself at that point. This direction is given by the wave-normal at that point.

The direction in which light is propagated is called a ray of light. Only in a homogeneous isotropic medium is a ray of light the same as a wave-normal. For spherical wave-fronts spreading out from a point source, the rays are radially divergent.
A plane wave-front may be treated as part of spherical (or cylindrical) wave-front at a very great distance from a point source, such that the wave-front has negligible curvature. The rays corresponding to a plane wave-front form a parallel beam.


A. Huygens’ Principle: Every point on a wave-front acts as a secondary source of light and sends out secondary wavelets in all directions. The secondary wavelets travel with the speed of light in the medium and are effective only in the forward direction. At any instant, the forward-going envelope or the surface of tangency to these wavelets gives the position of the new wave-front at that instance.


A. A plane wave-front may be treated as a part of a spherical (or cylindrical) wave at a very great distance from a point or an extended source, such that the wave-front has negligible curvature. Let A, B, C, D, ... be points on a plane wave-front in a homogeneous isotropic medium in which the speed of light is \( v \).

In a time \( \Delta t \), secondary wavelets with the points A, B, C, D, ..., as secondary sources travel a distance \( v\Delta t \). To find the position of the wave-front after a time \( \Delta t \), we draw spheres of radii \( v\Delta t \) with A, B, C, ... , as centres. The envelope or the surface of tangency to these spheres is a plane \( A'B'C' \) and this plane is at a perpendicular distance \( v\Delta t \) from the original wave-front in the direction of the wave. Thus, in an isotropic medium, plane wave-fronts are propagated as planes.

Q. 10. Explain Huygens’ construction of a spherical wave-front.

A. Consider a point source of light S in a homogeneous isotropic medium. The light waves travel with the same speed \( v \) in all directions. After time \( t \), the wave will reach all the points which are at a distance \( vt \) from S. This is the spherical wave-front. Let A, B, C, ..., be points on the wave-front. To find the new wave-front after a time \( \Delta t \), we draw spheres of radius \( v\Delta t \) with A, B, C, ..., as centres. The envelope or surface of tangency of these spheres is the surface \( A'B'C' \). This is the new spherical wave-front. Thus, in an isotropic medium spherical wave-fronts are propagated as concentric spheres.

Q. 11. Explain the phenomenon of reflection on the basis of Huygens’ wave theory of light.
A. Consider a plane wave-front of monochromatic light incident obliquely on a plane mirror PQ. \(A_1B_1, A_2B_2\) and AB are the successive positions of the incident wave-front one wavelength apart; \(A_1A\) and \(B_1B\) are the corresponding incident rays of light.

When the wave-front AB is incident on the mirror, at first, the point A becomes a secondary source and emits secondary waves in the same medium. Let \(v\) be the speed of light in the medium. If \(t\) is the time taken by the incident wave-front to travel from B to C, then \(BC = vt\). During this time secondary waves originating at A cover the same distance, so that the secondary spherical wavelet has a radius \(vt\).

With A as the centre, draw a hemisphere of radius \(vt\), to represent the secondary wavelet originating from A. Draw a tangent CD to the secondary wavelet.

As all points on CD are in the same phase of wave motion, CD represents the reflected wave-front. It travels parallel to itself taking successive positions \(C_1D_1, C_2D_2\) etc. therefore, \(AD_2\) and \(CC_2\) represent the reflected rays. If a normal AN is drawn to PQ, \(\angle A_1AN = \theta = \text{angle of incidence}\) and \(\angle NAD = r' = \text{angle of reflection}\).

From the geometry of the figure, it can be shown that the angle of incidence is equal to the angle of reflection. Also, it can be seen from the figure that the incident ray and the reflected ray lie on the opposite sides of the normal to the reflecting surface at the point of incidence and all of them are in the same plane.

Thus, reflection of light can be explained on the basis of Huygens’ wave theory.


A. Consider a plane wave-front of monochromatic light obliquely incident at a plane refracting surface PQ separating two mediums. Let, \(A_1B_1, A_2B_2\), and AB, be the successive positions of the incident wave-front one wavelength apart, and \(A_1A\) and \(B_1B\), the corresponding incident rays. When the wave-front reaches the point A, it becomes a secondary source and emits secondary waves in the second medium.

Let \(v_1\) and \(v_2\) be the speeds of light in the medium 1 (say, a rarer medium) and the medium 2 (a denser medium) respectively. If \(t\) is the time taken by the incident ray to cover the distance BC, then \(BC = v_1t\). During this time, the secondary wavelets originating at A cover a distance \(v_2t\) in the denser medium. Therefore, the secondary spherical wavelet has radius \(v_2t\).
With A as the centre, draw a hemisphere of radius \(v_2 t\) in the denser medium. It represents the secondary wave-front originating at A. Draw a tangent CD to the secondary wave-front.

As all points on CD are in the same phase of wave motion, CD represents the refracted wave-front in the denser medium. It travels parallel to itself, taking successive positions \(C_1 D_2, C_2 D_2,\) etc. \(AD_2\) and \(CC_2\) represent the corresponding refracted rays. Draw \(NAM\) normal to \(PQ.\)

Now, \(\angle A_1 AN = i = \text{angle of incidence}\) and \(\angle MAD = r = \text{angle of refraction}.\)

From the figure, \(\angle A_1 AN + \angle NAB = 90^\circ\) and \(\angle NAB + \angle BAC = 90^\circ\)

\(\therefore \angle BAC = \angle A_1 AN = i\)

Also, \(\angle MAD + \angle DAC = 90^\circ\) and \(\angle DAC + \angle ACD = 90^\circ\)

\(\therefore \angle ACD = \angle MAD = r\)

From the \(\Delta BAC\) and \(\Delta ACD, \sin i = \frac{BC}{AC}\) and \(\sin r = \frac{AD}{AC}\)

\(\therefore \frac{\sin i}{\sin r} = \frac{BC}{AD} = \frac{v_1 t}{v_2 t} = \frac{v_1}{v_2}\)

By definition, the refractive index of medium 2 with respect to medium 1,

\(n_2 = \frac{\text{speed of light in medium 1}}{\text{speed of light in medium 2}}\)

\(\therefore n_2 = \frac{\sin i}{\sin r} = \text{constant for a given pair of mediums and a given frequency of incident light.}\)

This is Snell’s law of refraction.

Also it can be seen from the figure that the incident ray and the refracted ray lie on the opposite sides of the normal and all three of them lie in the same plane.

Thus, the laws of refraction of light can be explained on the basis of Huygens' wave theory.