

Module 1 : Huygens Principle and Interference

This module is designed to help you to:

- explain the meaning of phase and phase difference in wave motion;
- apply the concept of wavefront for explaining propagation of light waves;
- state and use the Huygens principle of secondary wavelets;
- describe interference of waves

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10.1.1 Introduction

Here, we first refresh the concepts of path; path difference and phase which one had to learn in connection with propagation of waves. We shall introduce the concept of traveling of light as propagation of transverse waves. We shall describe the phenomenon of propagation of waves in a medium in terms of Huygens principle of secondary wavelets. The laws of reflection and refraction are discussed using Huygens principle. We shall also introduce the phenomenon of interference of light.

10.1.2 Phase

The concept of phase plays a pivotal role in the understanding of the kinematics of an oscillating particle. Phase is a parameter that enables us to know the instantaneous state of an oscillating particle (position, speed, and direction of motion). We describe the phase of an oscillating particle, in terms of the circle of reference of a simple harmonic motion. Fig.10.1.1 shows particle P moving along the circle of reference with an angular velocity ω .

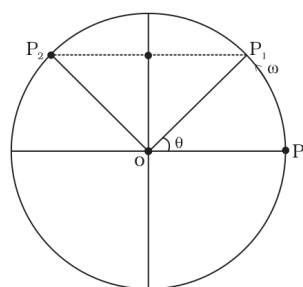


Fig.10.1.1 Particle P moving along the circle of reference with an angular velocity ω

The instantaneous projection of P on a vertical (or horizontal) diameter gives the instantaneous position of the particle in the SHM. The angle $\angle POP_0 = \theta$, the instantaneous radius vector OP, makes with the reference line OP_0 is as a measure of the instantaneous 'phase' of the particle executing SHM. For radii vectors OP_1 and OP_2 , the phase angle has values θ and $(\frac{\pi}{2} + \theta)$. These two values of phase angle, correspond to the two positions of the oscillating particle, for these two positions of P. Corresponding to the position P_1 , the oscillation particle (N) is moving upwards while corresponding to P_2 , it is moving downwards.

Phase values of $2\pi, 4\pi, 6\pi, \dots, 2n\pi$, indicate that the particle is back in its original state of oscillation. We, therefore, say that the state of oscillation of a particle repeats itself whenever its phase changes by any integral multiple of 2π . The particles having a phase difference of $2n\pi$, ($n = 0, 1, 2, 3, \dots$) are in phase.

Particles, having a phase difference of $\pi, 3\pi, 5\pi, \dots$ (i.e. $(2n+1)\pi$, at a given instant, would be in opposite states of oscillation. Therefore oscillating particles, having a phase difference of $(2n+1)\pi$ ($n = 0, 1, 2, 3, \dots$) are in out of phases (i.e., in opposite states of oscillation).

10.1.3 Waves, wavelength

Propagation of a (mechanical) wave, in a medium, occurs due to the transfer of a disturbance, imparted to one particle of the medium. The propagation disturbance (or oscillations) occurs at a finite speed in a given medium. Two successive particles of the medium are not in the same state of oscillation (i.e. in the same phase) at a given instant of time. This difference in phase keeps on increasing as the disturbance propagates through the medium. For a particular distance of propagation, the phase difference between the originally disturbed particle, and the particle just receiving this disturbance, becomes equal to 2π . These particles are in the same phase, i.e. the same state of oscillation, as the originally disturbed particle. The minimum separation of these two particles (having a phase difference of 2π with respect to the originally disturbed particle), is known as the wavelength (λ) of the wave.

10.1.4 Relation between phase difference and path difference

The separation Δ , between the two particles of the medium is known as their path difference. The phase difference between the two particles is

$$\text{Phase difference } (\phi) = \frac{2\pi}{\text{wavelength}} (\text{Path difference})$$

$$\phi = \frac{2\pi}{\lambda} (\Delta) \quad (10.1.1)$$

Hence, the phase difference between two points, given by $x = x_1$ and $x = x_2$ will be

$$\phi = \frac{2\pi}{\lambda} (x_2 - x_1) \quad (10.1.2)$$

A path difference, of wavelength (λ), corresponds to a phase difference of 2π . The above relations are very useful to understand and appreciate the phenomenon of interference and diffraction.

10.1.5 Huygens principle

Consider a point source emitting 3-D waves uniformly in all directions. At a given time $t = t$ the loci of all points of the medium in the same phase is a sphere [Fig. 10.1.1]. This is the wavefront at this moment of time.

According to Huygens principle; each point of a wavefront is the source of a secondary disturbance and the wavelets, emanating from these points, spread out in all directions with the speed of the wave. The wavelets emanating from the wavefront are usually referred to as *secondary wavelets*. The tangential surface to the secondary wavelets, is the position of the new wavefront (Fig. 10.1.2).

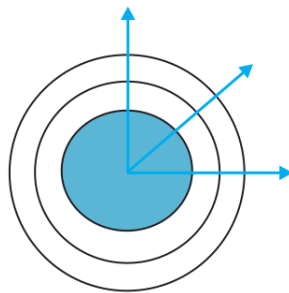


Fig. 10.1.2 A diverging spherical wave emanating from a point source. The wavefronts are spherical.

Wavefronts can be of different types depending on the shape of the source of light.

The wavefront is *spherical*, for a point source of light, with the point source at its centre.

The wavefront is *cylindrical* for a linear source of light, with all the points equidistant from the source.

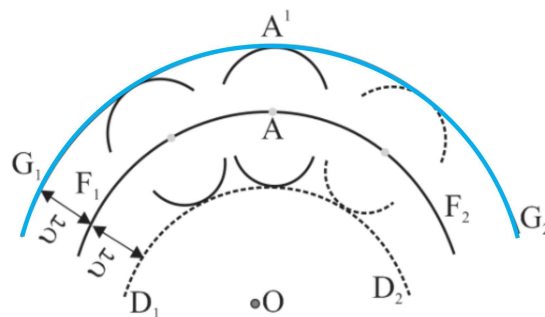


Fig. 10.1.3 The envelope of the secondary wavelets emanating from F_1F_2 produces the forward-moving wavefront G_1G_2 . The back wave D_1D_2 does not exist because we take only the advancing wavefronts.

For points very far off from the source, a small portion of a spherical or a cylindrical wavefront appears as a plane wavefront. Fig.10.1.4 shows the propagation of a plane wavefront in terms of Huygens Principle.

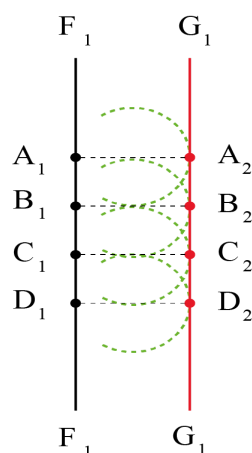


Fig. 10.1.4 Geometrical construction for a plane wave propagating along the right direction.

Activity 10.1.1 Students need to be facilitated to perform the activity.

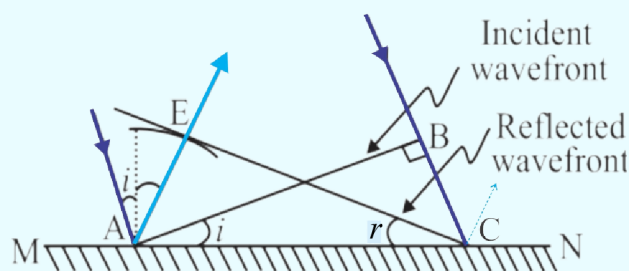


Fig. 10.1.5 Reflection of a plane wave AB by the reflecting surface MN . AB and CE represent incident and reflected wavefronts.

Refer to Fig. 10.1.6 above and construct a spherical wavefront with A as centre and radius equal to BC . While ray from B reaches C , the secondary wavelets from point A would travel a distance $AE = BC$. The new wavefront is the tangent drawn from point C to the position of secondary wavelets from A .

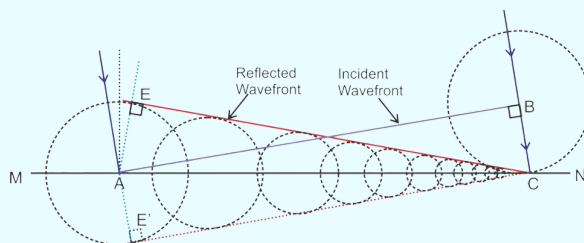


Fig. 10.1.6

1. Forward directions: The reflected wavefront is EC. This is the propagation of incident wavefront AB within time in which B reaches C. (This would be wavefront direction in the absence of a reflecting surface).
2. Backward directions: Wavefront E'C would represent reflection from A in time, in which wave B reaches C.

Activity 10.1.2

Construct a further spherical wavefront that would start from EC (with A and C as centers) and advance a distance $c \Delta t$ in time Δt . The common tangent $E'C'$ would represent the new wavefront after time Δt of starting from EC (Fig. 10.1.7).

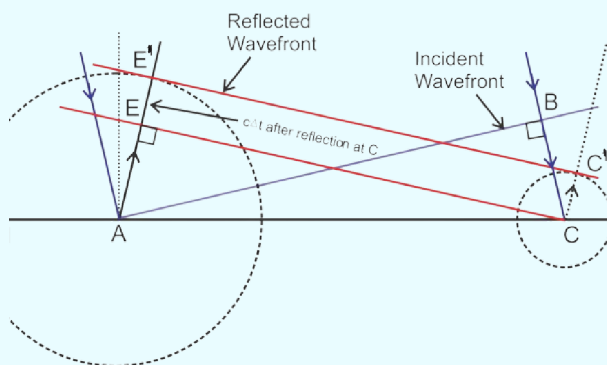


Fig. 10.1.7

Activity 10.1.3

Repeat activity 10.1.2 for refraction referring to Fig. 10.1.8 shown below to understand advancement of plane wavefront in time $(\frac{BC}{c})$ and then over a further time Δt , as in case of activity 1. [Assume $v = \frac{2}{3}c$]

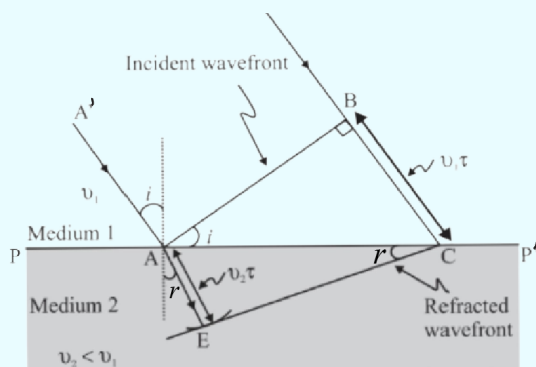


Fig. 10.1.8

A plane wave AB is incident at an angle i on the surface PP' separating medium 1 and 2. The plane wave undergoes refraction and CE represents the refracted wavefront. (Fig. 10.1.8) corresponds to $v_2 < v_1$; the refracted waves bend towards the normal.

10.1.6 Coherent sources and interference of lights

Coherent Sources

Two sources are said to be coherent if they emit waves of the same frequency, nearly the same amplitude, and are in the same phase, (or have a constant phase difference). It means that the two sources must emit radiation of the same wavelength. In actual practice, it is not possible to have two independent sources which are coherent. For experimental purposes, two secondary sources, 'formed/derived' from a single source, can act as coherent sources.

Interference of light

The redistribution of light energy due to the superposition of two or more waves is known as interference of light. *Constructive* interference occurs when the optical path difference between the waves is an integral multiple of the wavelength (waves differ in phase by an integral multiple of 2π). This means at the given point if there is a crest (trough) due to one source, there is a crest(trough) due to the other source also, resulting in enhancing the overall effect; this is *constructive interference*. For *destructive interference*, the path difference is an odd integral multiple of half the wavelength (waves differ in phase by odd integral multiples of π). This means at the given point if there is a crest (trough) due to one source, there is a trough(crest) due to the other source also, resulting in a reduced overall effect.

Example 10.1.1

In Fig. 10.1.9 S_1 and S_2 are two coherent point sources, obtained from a single point source S, S_1 and S_2 are in the same phase. Path length $S_1P = x_1$ and $S_2P = x_2$. Find out the resultant effect at point P (bright or dark?) if

- (i) $x_1 = 3\lambda$ and $x_2 = 4\lambda$
 (ii) $x_1 = 5\lambda$ and $x_2 = 6.5\lambda$

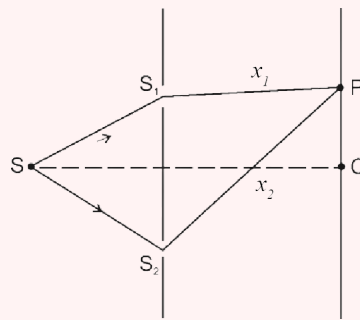


Fig. 10.1.9

Solution

Let ϕ_1 and ϕ_2 be the phases at $x = x_1$ and $x = x_2$

Δ = The path difference = $x_2 - x_1$

(i) $\Delta = 4\lambda - 3\lambda = \lambda$

The path difference is an integral multiple of λ .

The resultant effect is that P is bright.

(ii) $\Delta = 6.5\lambda - 5\lambda = 1.5\lambda$

The path difference is an odd multiple of λ

The resultant effect is that P is dark.

Example 10.1.2

The waves emitted by S_1 and S_2 shown above in Fig.10.1.9 are represented by

$$E_1 = E_0 \sin \left(\omega t - \frac{2\pi x_1}{\lambda} \right) \text{ and } E_2 = E_0 \sin \left(\omega t - \frac{2\pi x_2}{\lambda} \right)$$

What is resultant intensity at P for $x_1 = 11\lambda$ and $x_2 = \frac{89}{8}\lambda$

Solution $E = E_1 + E_2 = 2E_0 \sin[\omega t] \cos \frac{2\pi}{\lambda} [x_1 + x_2]$

$$= 2E_0 \sin[\omega t] \cos \frac{2\pi}{\lambda} [11\lambda + \frac{89}{8}\lambda]$$

$$= 2E_0 \sin[\omega t] \cos [22\pi + \frac{\pi}{2}] = 0$$



Let Us Reflect

Q.10.1.1 At a given point on a wavefront the phase is $\frac{\pi}{3}$. What is the phase at the same point when the wavefront advances by a distance $\frac{3\lambda}{2}$?

Q.10.1.2 What is the shape of the wavefront corresponding to sunlight reaching the surface of the earth?

Q.10.1.3 When a light wave travels from one medium to another, which among the following: velocity, wavelength and frequency, does not change?



Answers

A.10.1.1

$\Delta\phi$ is the change in phase for a change in path $\Delta = \frac{3\lambda}{2}$

$$\Delta\phi = \frac{2\pi}{\lambda} \cdot \Delta x = \frac{2\pi}{\lambda} \times \frac{3\lambda}{2} = 3\pi. \text{ The final phase } \phi = \frac{\pi}{3} + 3\pi = \frac{10\pi}{3}$$

A.10.1.2 Originally the waves are spherical, but due to their travel for a very large distance, the sphere spreads out to take the planar form. so, the wavefront is plane.

A.10.1.3 Frequency does not change as it depends on the source.

10.1.7 Summary

- Phase in SHM, gives complete information regarding the state of motion, governed by way of simultaneous consideration of the position and velocity of the particle considered.
- The phase difference $\Delta\phi$ between two points at $x = x_1$ and $x = x_2$ is

$$\Delta\phi = \frac{2\pi}{\lambda}(x_2 - x_1).$$

- The wavefront at $t = t$ is the locus of all the points of the medium in the same phase
- For a point source wavefront with source is at the centre of the sphere.
- For a thin line source the wavefront is cylindrical with wire at its axis.
- According to Huygens' principle of secondary wavelets
 - (i) every point on the given wavefront is an imaginary point source. The disturbance from the point source is known as a secondary wavelet.
 - (ii) The tangential plane to the secondary wavelets is the new wavefront.
- Two sources of a wave having the same wavelength and same/nearly the same amplitude and zero or a constant phase difference are known as coherent sources.
- The redistribution of energy in a medium due superimposition of two or more waves is known as interference.
- (i) constructive interference
 - phase difference $\Delta\phi = 2n\pi$
 - path difference $\Delta = n\lambda$ $n = 0, 1, 2, 3, \dots$
- (ii) destructive interference
 - phase difference $\Delta\phi = (2n-1)\pi$
 - path difference $\Delta = (2n-1)\frac{\lambda}{2}$ $n = 1, 2, 3, \dots$



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