312en22

22

WAVE PHENOMENA AND LIGHT

In the preceding two lessons of this module, you studied about reflection, refraction, dispersion and scattering of light. To understand these, we used the fact that light travels in a straight line. However, this concept failed to explain redistribution of energy when two light waves were superposed or their bending around corners. These observed phenomena could be explained only on the basis of wave nature of light. Christian Huygens, who was a contemporary of Newton, postulated that light is a wave and the wave theory of light was established beyond doubt through experimental observations on interference and diffraction. In this lesson, you will also learn about polarisation, which conclusively proved that light is a wave and transverse in nature.

OBJECTIVES

After studying this lesson, you should be able to :

- *state Huygens' principle and apply it to explain wave propagation*;
- *explain the phenomena of interference and diffraction of light*;
- *explain diffraction of light by a single-slit; and*
- *show that polarisation of light established its wave nature; and*
- *derive Brewster's law.*

22.1 HUYGENS' PRINCIPLE

Huygens' postulated that light is a wave, which travels through a hypothetical medium called ether. This hypothetical medium has the strange property of occupying all space, including vacuum! The vibrations from the source of light propagate in the form of waves and the energy carried by them is distributed equally in all directions.

The concept of wavefront is central ***Huygens'principle.*** Let us first understand what a wavefront is with the help of a simple activity.

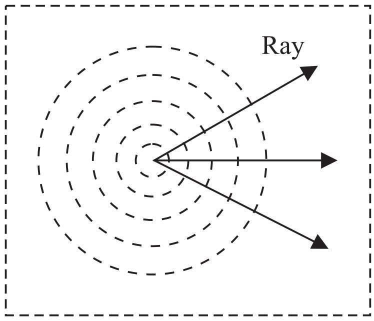

Fig. 22.1: Circular wavefronts on the surface of water

ACTIVITY 22.1

Take a wide based trough full of water and drop a small piece of stone in it. What do you observe? You will see that circular ripples due to the up and down motion of water molecules spread out from the point where the stone touched the water surface. If you look carefully at these ripples, you will notice that each point on the circumference of any of these ripples is in the same state of motion i.e., each point on the circumference of a ripple oscillates with the same amplitude and in the same phase. In other words, we can say that *the circumference of a ripple is the locus of the points vibrating in the same phase at a given instant and is known as* ***the wavefront.*** Therefore, the circular water ripples spreading out from the point of disturbance on the water surface represent a **circular wavefront.** Obviously, the distance of every point on a wavefront is the same from the point of disturbance, i.e., the source of waves.

For a point source emitting light in an isotropic medium, the locus of the points where all waves are in the same phase, will be a sphere. Thus, a point source of light ***emits spherical wavefronts.*** (In two dimensions, as on the water surface, the wavefronts appear circular.) Similarly, a line source of light emits ***cylindrical wavefronts.*** *The line perpendicular to the wavefront at a point represents the direction of motion of the wavefront at that point. This line is called the ray of light and a collection of such rays is called a beam of light.* When the source of light is at a large distance, any small portion of the wavefront can be considered to be a ***plane wavefront.***

The ***Huygens'principle*** states that

- Each point on a wavefront becomes a source of secondary disturbance which spreads out in the medium.
- The position of wavefront at any later instant may be obtained by drawing a forward common envelop to all these secondary wavelets at that instant.
- In an isotropic medium, the energy carried by waves is transmitted equally in all directions.

- If the initial shape, position, the direction of motion and the speed of the wavefront is known, its position at a later instant can be ascertained by geometrical construction. Note that the wavefront does not travel in the backward direction.

To visualise Huygens' construction, you may imagine a point source at the centre of a hollow sphere. The outer surface of this sphere acts as a primary wavefront. If this sphere is enclosed by another hollow sphere of larger radius, the outer surface of the second hollow sphere will act as a secondary wavefront. (The nearest mechanical analogue of such an arrangement is a football.) If the second sphere is further enclosed by another sphere of still bigger radius, the surface of the outermost (third) sphere becomes secondary wavefront and the middle (second) sphere acts as the primary wavefront. In two dimensions, the primary and secondary wavefronts appear as concentric circles.

22.1.1 Propagation of Waves

Now let us use Huygens' principle to describe the propagation of light waves in the form of propagation of wavefronts. Fig. 22.2 shows the shape and location of a plane wavefront *AB* at the time $t = 0$. You should note that the line *AB* lies in a plane perpendicular to the plane of the paper. Dots represented by *a*, *b*, *c*, on the wavefront *AB* are the sources of secondary wavelets. All these sources emit secondary wavelets at the same time and they all travel with the same speed along the direction of motion of the wavefront *AB*. In Fig. 22.2, the circular arcs represent the wavelets emitted from *a*, *b*, *c*, … taking each point as center. *These wavelets have been obtained by drawing arcs of radius*, $r = \upsilon t$, *where* υ *is the velocity of the wavefront and t is the time at which we wish to obtain the wavefront*, The tangent, *CD*, to all these wavelets represents the new wavefront at time $t = T$.

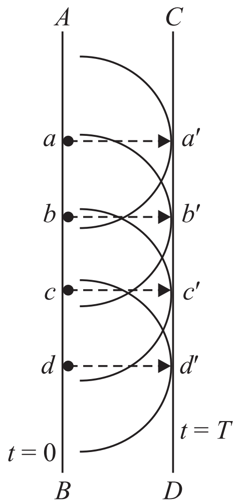

Fig. 22.2: Construction of a plane wave front

Let us take another example of Huygens' construction for an expanding circular wavefront. Refer to Fig. 22.3, which indicates a circular wavefront, centred at *O*, at time $t = 0$. Position *A*, *B*, *C* … represent point sources on this wavefront. Now to draw the wavefront at a later time $t = T$, what would you do? You should draw arcs from the points *A*, *B*, *C* …, of radius equal to the speed of the expanding wavefront multiplied by *T*. These arcs will

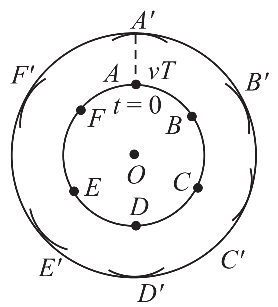

Fig. 22.3: Construction of circular wavefront using Huygens' principle

represent secondary wavelets. The tangents drawn to these arcs will determine the shape and location of the expanding circular wavefront at time T.

We hope you have now understood the technique of Huygens' construction. Now, you may like to know the ***physical significance of Huygens' construction.*** By determining the shape and location of a wavefront at a subsequent instant of time with the help of its shape and location at an earlier instant, we are essentially describing the propagation of the wavefront. Therefore, Huygens' construction enables us to describe wave motion.

INTEXT QUESTIONS 22.1

1. What is the relative orientation of a wavefront and the direction of propagation of the wave?
2. A source of secondary disturbance is emitting wavelets at an instant $t = 0$ s. Calculate the ratio of the radii of wavelets at $t = 3$s and $t = 6$s.

22.2 INTERFERENCE OF LIGHT

Let us first perform a simple activity:

ACTIVITY 22.2

Prepare a soap solution by adding some detergent powder to water. Dip a wire loop into the soap solution and shake it. When you take out the wire loop, you will find a thin film on it. Bring this soap film near a light bulb and position yourself along the direction of the reflected light from the film. You will observe beautiful colours. Do you know the reason? To answer this question, we have to understand the phenomenon of ***interference of light.*** In simple terms, ***interference of light refers to redistribution of energy due to superposition of light waves from two coherent sources.*** The phenomenon of interference of light was first observed experimentally by Thomas Young in 1802 in his famous two-slit experiment. This experimental observation played a significant role in establishing the wave theory of light. The basic theoretical principle involved in the phenomenon of interference as well as diffraction of light is the *superposition principle*.

22.2.1 Young's Double Slit Experiment

Young's experimental set up is shown schematically in Fig. 22.4. In his experiment, sunlight was allowed to pass through a pin hole S and then, at some distance away, through two pin holes S_1 and S_2 equidistant from S and close to each other.

According to Huygens' wave theory of light, spherical wavefronts would spread out from the pin hole S which get divided into two wavefronts by S_1 and S_2. If S is illuminated by a monocromatic source of light, such as sodium, these act as coherent sources and in-phase waves of equal amplitude from these sources superpose as they move beyond S_1S_2. As a consequence of superposition (of the two sets of identical waves from S_1 and S_2), redistribution of energy takes place and a pattern consisting of alternate bright and dark fringes is produced on the screen such as placed at C. Let us now learn the explanation of the observed fringe pattern in the Young's interference experiment.

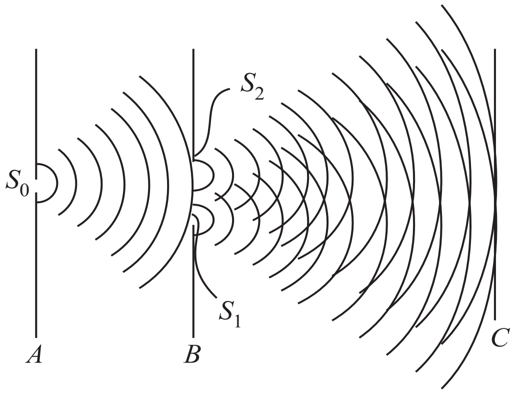

Fig. 22.4: Schematic arrangement of Young's double-slit experiment

Euygene Thomas Young (1773-1829)

Born on 16 June, 1773, Euygene Thomas Young will always be known for his study on the human ear, the human eye, how it focuses and on astigmatism. His research on colour blindness led him to the three component theory of colour vision. Working on human ears and eyes, he dedicated much time to the speed of sound and light. He knew that if two sound waves of equal intensity reached the ear 180º out of phase, they cancelled out each other's effect and no sound was heard. It occurred to him that a similar interference effect should be observed with two light beams, if light consisted of waves. This led Young to devise an experiment, now commonly referred to as the Young's double-slit experiment.

In his later years, Young devoted most of his time deciphering the Egyptian hieroglyphics found on the Rosetta stone discovered in the Nile Delta in 1799.

(a) Constructive Interference: You may recall from the superposition principle that some points on the screen *C* will have maximum displacement (or amplitude) because the crests due to one set of waves coincide with the crests due to another set of waves. In other words, at this point, the waves arrive in-phase and hence the total amplitude is much higher than the amplitude of individual waves. The same holds true for the points where the troughs due to one set of waves coincide with the troughs due to another set. Such points will appear bright because the intensity of light wave is proportional to the square of the amplitude. Superposition of waves at these points leads to what is known as ***constructive interference.***

(b) Destructive Interference: The points where the crests due to one set of waves coincide with the troughs due to the other set and vice-versa, the total amplitude is zero. It is so because the waves reach these points completely out of phase. Such points appear dark on the screen. These points correspond to ***destructive interference.***

(c) Intensity of fringes: To analyse the interference pattern, we calculate the intensity of the bright and dark fringes in the interference pattern for harmonic waves. Refer to Fig. 22.5, which is schematic representation of the geometry of Young's experiment. The phenomenon of interference arises due to superposition of two harmonic waves of same frequency and amplitude but differing in phase. Let the phase difference between these two waves be δ. We can write y_1 and y_2, the displacements at a fixed point *P* due to the two waves, as

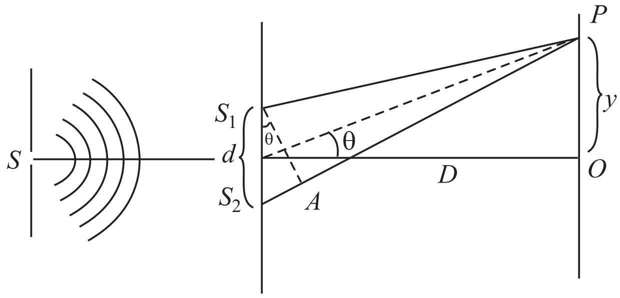

Fig. 22.5: Geometry of Young's double slit experiment

$$y_1 = a \sin \omega t$$

and $$y_2 = a \sin (\omega t + \delta)$$

where δ signifies the phase difference between these waves. Note that we have not included the spatial term because we are considering a fixed point in space.

According to the principle of superposition of waves, the resultant displacement is given by

$$\begin{aligned} y &= y_1 + y_2 \\ &= a \sin \omega t + a \sin (\omega t + \delta) \\ &= a [\sin \omega t + \sin (\omega t + \delta)] \\ &= 2a \sin (\omega t + \frac{\delta}{2}) \cos \left(-\frac{\delta}{2}\right) \\ &= A \sin (\omega t + \frac{\delta}{2}) \end{aligned}$$

where amplitude of the resultant wave is given by

$$A = 2a \cos (\delta/2).$$

The intensity of the resultant wave at point P can be expressed as

$$I \propto A^2$$

$$\propto 4a^2 \cos^2 (\delta/2) \qquad (22.1)$$

To see the dependence of intensity on the phase difference between the two waves, let us consider the following two cases.

Case 1: When the phase difference, $\delta = 0, 2\pi, 4\pi, \ldots, 2n\pi$

$$I = 4a^2 \cos^2 0$$

$$= 4a^2$$

Case 2: When, $\delta = \pi, 3\pi, 5\pi, \ldots\ldots, (2n+1)\pi$

$$I = 4a^2 \cos^2 (\delta/2)$$

$$= 0$$

From these results we can conclude that when phase difference between superposing waves is an integral multiple of 2π, the two waves arrive at the screen 'in-phase' and the resultant intensity (or the brightness) at those points is more than that due to individual waves (which is equal to $4a^2$). On the other hand, when phase difference between the two superposing waves is an odd multiple of π, the two superposing waves arrive at the screen 'out of phase'. Such points have zero intensity and appear to be dark on the screen.

(d) Phase Difference and Path Difference

It is obvious from the above discussion that to know whether a point on the screen will be bright or dark, we need to know the phase difference between the waves arriving at that point. The phase difference can be expressed in terms of the path difference between the waves during their journey from the sources to a point on the observation screen. You may recall that waves starting from S_1 and S_2 are in phase. Thus, whatever phase difference arises between them at the point P is because of the different paths travelled by them upto observation point from S_1 and S_2. From Fig. 22.5, we can write the path difference as

$$\Delta = S_2P - S_1P$$

We know that path difference of one wavelength is equivalent to a phase difference of 2π. Thus, the relation between the phase difference δ and the path difference Δ is

$$\Delta = \left(\frac{\lambda}{2\pi}\right)\delta \qquad (22.2)$$

From Eqn. (22.1) we note that bright fringes (corresponding to constructive interference) are observed when the phase difference is $2n\pi$. Using this in Eqn. (22.2) we find that the path difference for observing bright fringes is

$$(\Delta)_{\text{bright}} = \left(\frac{\lambda}{2\pi}\right) 2n\pi = n\lambda; \; n = 0, 1, 2, \ldots \qquad (22.3)$$

Similarly, for dark fringes, we get

$$(\Delta)_{\text{dark}} = (\lambda/2\pi)\,(2n+1)\,\pi$$

$$= (2n+1)\frac{\pi}{2}; \; n = 0, 1, 2, \ldots \qquad (22.4)$$

Having obtained expressions for the bright and dark fringes in terms of the path difference and the wavelength of the light used, let us now relate path difference with the geometry of the experiment, i.e., relate Δ with the distance D between the source and the screen, separation between the pin holes (d) and the location of the point P on the screen. From Fig. 22.5 we note that

$$\Delta = S_2P - S_1P = S_2A = d\sin\theta$$

Assuming θ to be small, we can write

$$\sin\theta \approx \tan\theta \approx \theta$$

and

$$\sin\theta = x / D$$

Therefore, the expression for path difference can be rewritten as

$$\Delta = d\sin\theta = x\frac{d}{D} \qquad (22.5)$$

On substituting Eqn. (22.5) in Eqns. (22.2) and (22.3), we get

$$\frac{d}{D}(x_n)_{\text{bright}} = n\lambda$$

or

$$(x_n)_{\text{bright}} = \frac{n\lambda D}{d}; \; n = 0, 1, 2, \ldots \qquad (22.6)$$

and

$$\frac{d}{D}(x_n)_{\text{dark}} = \left(n + \frac{1}{2}\right)\lambda$$

or

$$(x_n)_{\text{dark}} = \left(n + \frac{1}{2}\right)\frac{\lambda D}{d}; \; n = 0, 1, 2, \ldots \qquad (22.7)$$

Eqns. (22.6) and (22.7) specify the positions of the bright and dark fringes on the screen.

(e) Fringe width

You may now ask: How wide is a bright or a dark fringe? To answer this question, we first determine the location of two consecutive bright (or dark) fringes. Let us first do it for bright fringes. For third and second bright fringes, from Eqn. (22.6), we can write

$$(x_3)_{\text{bright}} = 3\,\frac{\lambda D}{d}$$

and

$$(x_2)_{\text{bright}} = 2\,\frac{\lambda D}{d}$$

Therefore, fringe width, β is given by

$$\beta = (x_3)_{\text{bright}} - (x_2)_{\text{bright}} = \frac{\lambda D}{d} \qquad (22.8)$$

You should convince yourself that the fringe width of an interference pattern remains the same for any two consecutive value of n. Note that fringe width is directly proportional to linear power of wavelength and distance between the source plane and screen and inversely proportional to the distance between the slits. In actual practice, fringes are so fine that we use a magnifying glass to see them.

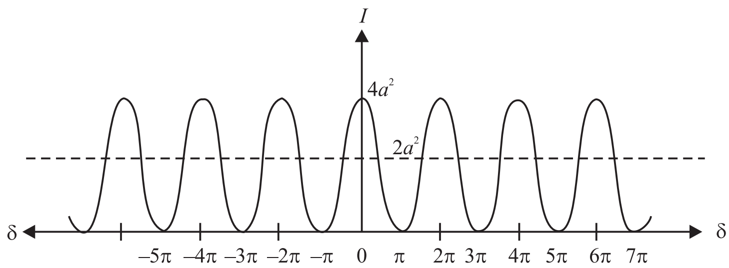

Fig. 22.6: Intensity distribution in an interference pattern

Next let us learn about the intensity of bright and dark fringes in the interference pattern. We know that when two light waves arrive at a point on the screen out of phase, we get dark fringes. You may ask : Does this phenomenon not violate the law of conservation of energy because energy carried by two light waves seem to be destroyed? It is not so; the energy conservation principle is not violated in the interference pattern. Actually, the energy which disappears at the dark fringes reappears at the bright fringes. You may note from Eqn. (22.1) that the intensity of the bright fringes is four times the intensity due to an individual wave. Therefore, in an interference fringe pattern, shown in Fig. (22.6), **the energy is redistributed and it varies between 4a^2 and zero.** Each beam, acting independently, will contribute a^2 and hence, in the absence of interference, the screen will be uniformly illuminated with intensity $2a^2$ due to the light coming from two identical sources. This is the average intensity shown by the broken line in Fig. 22.6.

You have seen that the observed interference pattern in the Young's experiment can be understood qualitatively as well as quantitatively with the help of wave theory of light. To be sure that you have good understanding, answer the following intext questions.

Notes

INTEXT QUESTIONS 22.2

1. On what factors does the resultant displacement at any point in the region of superposition of two waves depend?
2. In Young's experiment, how is the constructive interference produced on the screen?
3. If we replace the pinholes S_1 and S_2 by two incandescent light bulbs, can we still observe the bright and dark fringes on the screen?
4. What are coherent sources? Can our eyes not act as coherent sources?

22.3 DIFFRACTION OF LIGHT

In earlier lessons, you were told that rectilinear propagation is one of the characteristics of light. The most obvious manifestation of the rectilinear propagation of light is in the formation of shadow. But, if you study formation of shadows carefully, you will find that, as such, these are not sharp at the edges. For example, the law of rectilinear propagation is violated when the light passes through a very narrow aperture or falls on an obstacle of very small dimensions. At the edges of the aperture or the obstacle, light bends into the shadow region and does not propagate along a straight line. ***This bending of light around the edges of an obstacle is known as diffraction.***

Before discussing the phenomenon of diffraction of light in detail, you may like to observe diffraction of light yourself. Here is a simple situation. Look at the street light at night and almost close your eyes. What do you see? The light will appear to streak out from the lamp/tube. This happens due to the diffraction (bending) of light round the corners of your eyelids.

Another way to observe diffraction is to use a handkerchief. Hold it close to your eyes and look at the Sun or a lamp. You will observe circular fringes, which form due to diffraction of light by small apertures formed by crissed-crossed threads.

In the above situations, the dimensions of the diffracting obstacle/aperture are very small. To observe diffraction, either of the following conditions must be satisfied:

a) The size of the obstacle or the aperture should be of the order of the wavelength of the incident wave.

Notes

b) *The separation between the obstacle or aperture and the screen should be considerably larger (a few thousand times) than the size of the obstacle or aperture.*

On the basis of the above observations, it is easy to understand why we normally do not observe diffraction of light and why light appears to travel in a straight line. You know that the wavelength of light is of the order of 10^{-6} m. Therefore, *to observe diffraction of light, we need to have obstacles or aperture having dimensions of this order!*

22.3.1 Diffraction at a Single Slit

Let us see how diffraction pattern appears for a simple opening like a single slit. Refer to Fig. 22.7. It shows the experimental arrangement for producing diffraction pattern. *S* is a monochromatic source of light. It is placed on the focal plane of a converging lens so that a plane wavefront is incident on a narrow slit. Another converging lens focusses light from different portions of the slit on the observation screen.

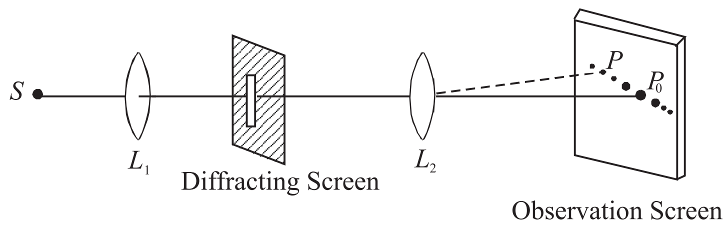

Fig. 22.7: Schematic representation of single slit dtiffraction

The salient features of the actual diffraction pattern produced by a single vertical slit from a point source as shown in Fig. 22.8 are :

- A horizontal streak of light along a line normal to the length of the slit.
- The horizontal pattern is a series of bright spots.

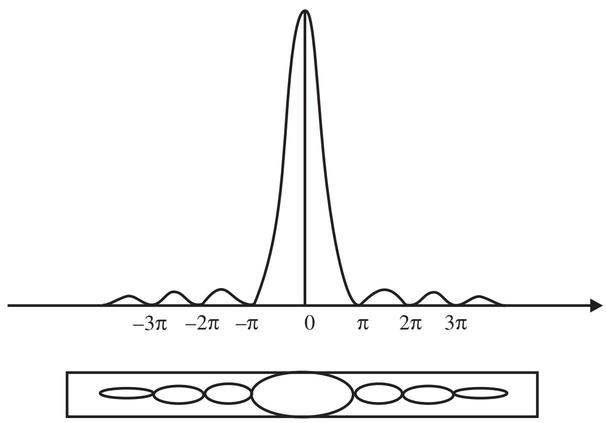

Fig. 22.8 : Observed differation pattern single of slit

- The spot at the centre is the brightest. On either side of this spot, we observe a few more symmetrically situated bright spots of diminishing intensity. The central spot is called *principal maxima* and other spots are called *secondary maxima.*
- The width of the central spot is twice the width of other spots.

To understand the theoretical basis of these results, we note that according to Huygens' wave theory, plane wavefronts are incident on the barrier containing the slit. As these wavefronts fall on the barrier, only that part of the wavefront passes through the slit which is incident on it. This part of the wavefront continues to propagate to the right of the barrier. However, the shape of the wavefront does not remain plane beyond the slit.

Refer to Fig. 22.9 which shows that each point of the aperture such as QPR ... Q′ form a series of coherent sources of secondary wavelets. In the central part of the wavefront to the right of the barrier, the wavelet emitted from the point *P*, say, spreads because of the presence of wavelets on its both sides emitted from the points such as *Q* and *R*. Since the shape of the wavefront is determined by the tangent to these wavelets, the central part of the wavefront remains plane as it propagates. But for the wavelets emitted from points *Q* and *Q′* near the edges of the slit, there are no wavelets beyond the edges with which these may superpose. Since the superposition helps to maintain the shape of the wavefront as plane, the absence of such superposing wavelets for the wavelets emitted from the points near the edges allows them to deviate from their plain shape. In other words, the wavelets at the edges tend to spread out. As a result, the plane wavefront incident on a thin aperture of finite size, after passing through it does not remain plane.

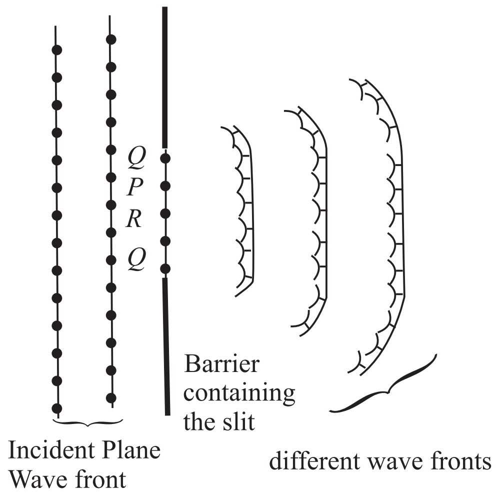

Fig. 22.9: Huygen's construction for diffraction of light from a narrow slit

To understa d the ***intensity distribution*** of the single-slit diffraction pattern, we determine the nature of the superposition of waves reaching the screen. In order to apply Huygens' principle, let us divide the width '*a*' of the slit into, say, 100 equal parts. Each of these can be considered as a sources of secondary wavelets. The wavelets emanating from these points spread out into the region to the right of the slit. Since the plane wavefront is incident on the slit, initially all points on it are in phase. Therefore, the wavelets emitted by these points are all in phase at the time of leaving the slit. Now let us consider the effect of the superposition of these wavelets at point O on the screen. The symmetry of the Fig. 22.10 suggests that the wavelets emitted from source of 1 and 100 will reach O in phase. It is so because both the wavelets travel equal path length. When they started their journey from the respective points on the slit, they were in phase. Hence they arrive at O in phase and superpose in such a manner as to give resultant amplitude much more than that due to the individual wavelets from the source 1 and 100. Similarly, for each wavelet from source 2 to 50, we have a corresponding wavelet from the source 99 to 51 which will produce constructive interference causing enhancement in intensity at the center O. Thus the point O will appear bright on the screen.

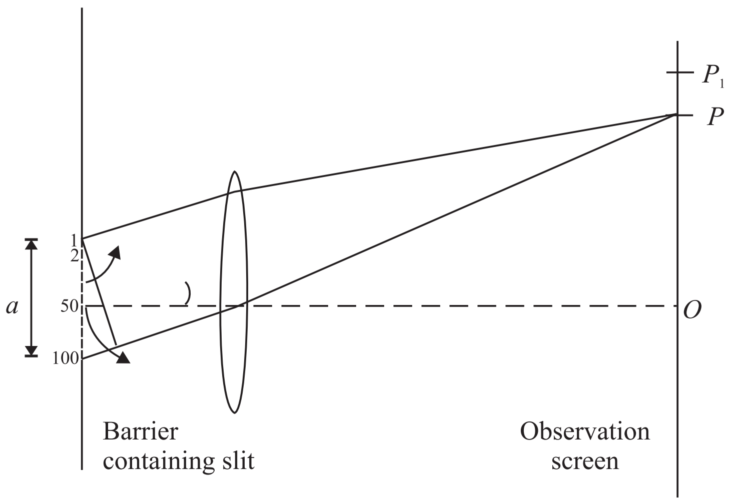

Fig. 22.10: Schematic representation of single slit diffraction

Now let us consider an off-axis point P on the observation screen. Suppose that point P is such that the *path difference* between the extreme points i.e. sources 1 and 100 is equal to λ. Thus the path difference between the wavelets from source 1 and 51 will be nearly equal to $(\lambda/2)$.

You may recall from the interference of light that the waves coming from the sources 1 and 51 will arrive at P out of phase and give rise to destructive interference. Similarly, wavelets from the sources 2 and 52 and all such pair of wavelets will give rise to destructive interference at the point P. Therefore, we will have minimum intensity at point P. Similarly, we will get minimum intensity for other points for which the path difference between the source edges is equal to 2λ. We can imagine that the slit is divided into four equal points and we can, by similar pairing of 1 and 26, 2 and 27, ... show that first and second quarters have a path difference of $\lambda/2$ and cancel each other. Third and fourth quarters cancel each other by the same argument so that the resultant intensity will be minimum, and so on. *We can therefore conclude that when the path difference between the extreme waves diffracted by the extreme points in a particular direction is an integral multiple of* λ*, the resultant diffracted intensity in that direction will be zero.*

Let us now find intensity at a point P' which lies between the points P and P_1 and the *path difference between waves diffracted from extreme points is* $3\lambda/2$. We divide the wavefront at the slit into 3 equal parts. In such a situation, secondary wavelets from the corresponding sources of two parts will have a path difference of $\lambda/2$ when they reach the point P and cancel each other. However, wavelets from the third portion of the wavefront will all contribute constructively (presuming that practically the path difference for wavelets from this part is zero) and produce brightness at P'. Since only one third of the wavefront contributes towards the intensity at P' as compared to O, where the whole wavefront contributes, the intensity at P' is considerably less than that of the intensity at O. The point P' and all other similar points constitute secondary maxima.

However, you must note here that this is only a qualitative and simplified explanation of the diffraction at a single slit. You will study more rigorous analysis of this phenomena when you pursue higher studies in physics.

INTEXT QUESTIONS 22.3

1. Does the phenomenon of diffraction show that the light does not travel along a straight line path?
2. Distinguish between interference and diffraction of light.
3. Why are the intensity of the principal maximum and the secondary maxima of a single slit diffraction not the same?

22.4 POLARISATION OF LIGHT

In the previous two sections of this lesson, you learnt about the phenomena of interference and diffraction of light. While discussing these phenomena, we did not bother to know the nature of light waves; whether these were longitudinal or transverse. However, polarisation of light conclusively established that light is a transverse wave.

To understand the phenomenon of polarisation, you can perform a simple activity.

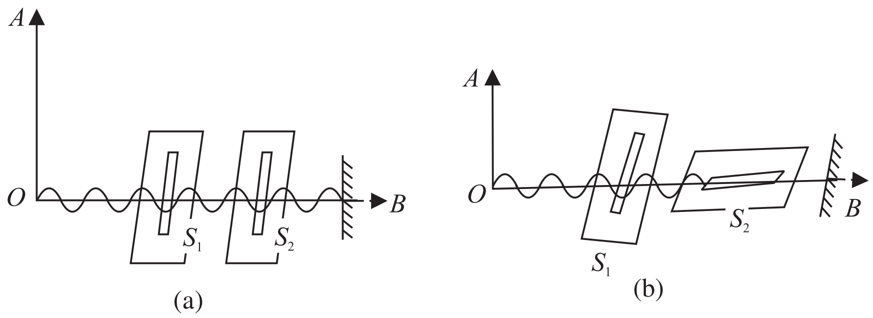

Fig. 22.11 : Transverse wave on a rope passing through a) two vertical slits, and b) one vertical and one horizontal slit

Take two card boards having narrow vertical slits S_1 and S_2 and hold them parallel to each other. Pass a length of a string through the two slits, fix its one end and hold the other in your hand. Now move your hand up and down and sideways to generate waves in all directions. You will see that the waves passing through the vertical slit S_1 will also pass through S_2, as shown in Fig. 22.11(a). Repeat the experiment by making the slit S_2 horizontal. You will see no waves beyond S_2. It means that waves passing through S_1 cannot pass through the horizontal slit S_2. This is because the vibrations in the wave are in a plane at right angles to the slits S_2, as shown in Fig. 22.11(b).

This activity can be repeated for light by placing a source of light at O and replacing the slits by two polaroids. You will see light in case(a) only. This shows that light has vibrations confined to a plane. It is said to be *linearly polarised* or *plane polarised* after passing through the first polaroid (Fig. 22.12).

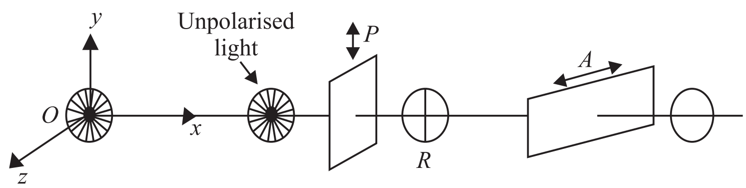

Fig. 22.12 : Schematics of the apparatus for observing polarisation of light

When an unpolarised light falls on glass, water or any other transparent material, the reflected light is, in general, partially plane polarised. Fig. 22.13 shows unpolarised light AO incident on a glass plate. The reflected light is shown by OR and the transmitted wave by OT. When the light is incident at polarising angle, the polarisation is complete. At this angle, the reflected and transmitted rays are at right angles to each other.

The polarising angle depends on the refractive index of the material of glass plate on which the (unpolarised) beam of light is incident. The relation between r and

i_p is obtained by using Snell's law (refer Fig. 22.13):

$$\mu = \frac{\sin i_p}{\sin r} = \frac{\sin i_p}{\sin(90 - i_p)}$$

$$= \frac{\sin i_p}{\cos i_p} == \tan i_p.$$

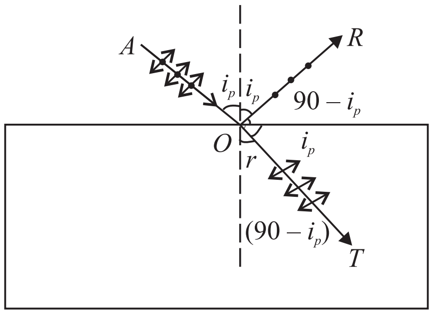

Fig. 22.13 : Polarisation of reflected and refracted light

This is known as ***Brewster's law.*** It implies that polarising angle i_p depends on the refractive index of the material. For air water interface, $i_p = 53°$. It means that when the sun is 37° above the horizontal, the light reflected from a calm pond or lake will be completely linearly polarised. Brewster's law has many applications in daily life. Glare caused by the light reflected from a smooth surface can be reduced by using polarising materials called *polaroids*, which are made from tiny crystals of quinine iodosulphate; all lined up in the same direction in a sheet of nitro cellulose. Such crystals (called dichoric) transmit light in one specific plane and absorb those in a perpendicular plan. Thus, *polaroid* coatings on sunglasses reduce glare by absorbing a component of the polarized light. Polaroid discs are used in photography as 'filters' in front of camera lens and facilitate details which would otherwise be hidden by glare. Polarimeters are used in sugar industry for quality control.

INTEXT QUESTIONS 22.4

1. Polarisation of light is the surest evidence that light is a transverse wave. Justify.
2. Is it correct to say that the direction of motion of a wave may not lie in the plane of polarisation?
3. Suppose a beam of unpolarised light is incident on a set of two *polaroids*. If you want to block light completely with the help of these polaroids, what should be the angle between the transmission axes of these polaroids?
4. Do sound waves in air exhibit polarization?

WHAT YOU HAVE LEARNT

- According to the Huygens' wave theory, light propagates in the form of wavefronts.
- The locus of all particles of the medium vibrating in the same phase at any instant of time is called the wavefront
- If two light sources emit light waves of the same frequency, same amplitude and move along the same path maintaining a constant phase difference between them, they are said to be coherent.
- When waves from two coherent sources superpose, a redistribution of energy takes place at different points. This is called the interference of light.
- For constructive interference, phase difference $\Delta = 2n\,\pi$ and for destructive interference, phase difference $\Delta = (2n + 1)\pi$.
- The bending of light near the corners of an obstacle or aperture is called diffraction of light.
- The phenomenon in which vibrations of light get confined in a particular plane containing the direction of propagation is called polarisation of light.

TERMINAL EXERCISE

1. Explain in brief the theories describing the nature of light.
2. What is a wavefront? What is the direction of a beam of light with respect to the associated wavefront? State the Huygens' principle and explain the propagation of light waves.
3. Obtain the laws of reflection on the basis of Huygens' wave theory.
4. What is the principle of superposition of waves? Explain the interference of light.
5. Describe Young's double slit experiment to produce interference. Deduce an expression for the width of the interference fringes.
6. What would happen to the interference pattern obtained in the Young's double slit experiment when
   (i) one of the slits is closed;
   (ii) the experiment is performed in water instead of air;
   (iii) the source of yellow light is used in place of the green light source;
   (iv) the separation between the two slits is gradually increased;

(v) white light is used in place of a monochromatic light;

(vi) the separation between the slits and the screen is increased;

(vii) two slits are slightly moved closer; and

(viii) each slit width is increased.

7. In Young's experimental set-up, the slit separation is 2 mm and the distance between the slits and the observation screen is 100 cm. Calculate the path difference between the waves arriving at a point 5 cm away from the point where the line dividing the slits touches the screen.

8. With the help of Huygens' construction, explain the phenomenon of diffraction.

9. How would you demonstrate that the light waves are transverse in nature?

10. Distinguish between the polarized and unpolarized lights.

11. State and explain Brewster's law.

12. The polarising angle for a medium is 60^o. Calculate the refractive index.

13. For a material of refractive index 1.42, calculate the polarising angle for a beam of unpolarised light incident on it.

ANSWERS TO INTEXT QUESTIONS

22.1

1. Perpendicular to each other ($\theta = \pi/2$) 2. ½

22.2

1. On the amplitude of the waves and the phase difference between them.

2. When the phase difference between the two superposing beams is an integral multiple of 2π, we obtain constructive interference.

3. No, it is so because two independent sources of light will emit light waves with different wavelengths, amplitudes and the two set of waves will not have constant phase relationship. Such sources of light are called incoherent sources. For observing interference of light, the sources of light must be coherent. When the light waves are coming from two incoherent sources, the points on the screen where two crests or two trough superpose at one instant to produce brightness may receive, at the other instant, the crest of the wave from one source and trough from the other and produce darkness. Thus, the whole screen will appear uniformly illuminated if the pinholes S_1 and S_2 are replaced by two incandescent light bulbs.

4. Coherent sources should emit waves

    (a) of same frequency and wavelength,

    (b) in phase or having constant phase difference, and

    (c) same amplitude and period.

    Moreover, these should be close. Our eyes may not meet this criterion.

22.3

1. Yes
2. Interference is the superposition of secondary waves emanating from two different secondary sources whereas diffraction is the superposition of secondary waves emanating from different portions of the same wavefronts.
3. Due to the increasing path difference between wavelets.

22.4

1. No. Because, in a longitudinal wave, the direction of vibrations is the same as the direction of motion of the wave.

2. No. 3. 90° or 270° 4. No.

Answers to Problems in Terminal Exercise

7. 0.1 mm 12. 1.73 13. 54°