Chapter 9

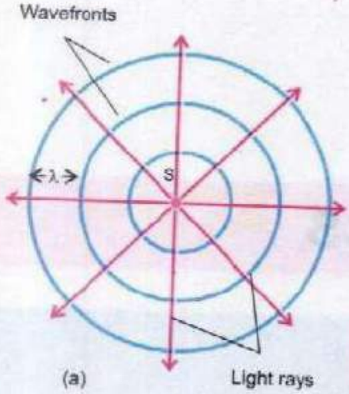
PHYSICAL OPTICS

Learning Objectives

At the end of this chapter the students will be able to:

1. Understand the concept of wavefront.
2. State Huygen's principle.
3. Use Huygen's principle to explain linear superposition of light.
4. Understand interference of light.
5. Describe Young's double slit experiment and the evidence it provided to support the wave theory of light.
6. Recognize and express colour patterns in thin films.
7. Describe the formation of Newton's rings.
8. Understand the working of Michelson's interferometer and its uses.
9. Explain the meaning of the term diffraction.
10. Describe diffraction at a single slit.
11. Derive the equation for angular position of first minimum.
12. Derive the equation $d \sin\theta = m\lambda$.
13. Carry out calculations using the diffraction grating formula.
14. Describe the phenomenon of diffraction of X-rays by crystals.
15. Appreciate the use of diffraction of X-rays by crystals.
16. Understand polarization as a phenomenon associated with transverse waves.
17. Recognize and express that polarization is produced by a Polaroid.
18. Understand the effect of rotation of Polaroid on polarization.
19. Understand how plane polarized light is produced and detected.

Light is a type of energy which produces sensation of vision. But how does this energy propagate? In 1678, Huygen's, an eminent Dutch scientist, proposed that



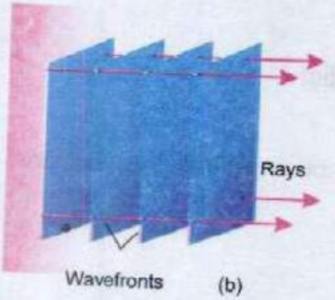


Fig. 9.1
Spherical wave fronts (a) and plane wavefronts(b)spaced a wavelength apart. The arrows represent rays.

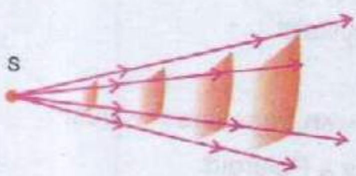
light energy from a luminous source travels in space as waves. The experimental evidence in support of wave theory in Huygen's time was not convincing. However, Young's interference experiment performed for the first time in 1801 proved wave nature of light and thus established the Huygen's wave theory. In this chapter you will study the properties of light, associated with its wave nature.

9.1 WAVEFRONTS

Consider a point source of light at S (Fig. 9.1 a). Waves emitted from this source will propagate outwards in all directions with speed c. After time t, they will reach the surface of an imaginary sphere with centre as S and radius as ct. Every point on the surface of this sphere will be set into vibration by the waves reaching there. As the distance of all these points from the source is the same, their state of vibration will be identical. In other words, all the points on the surface of the sphere will have the same phase.

Such a surface on which all the points have the same phase of vibration is known as wavefront.

Thus in case of a point source, the wavefront is spherical in shape. A line normal to the wavefront, showing the direction of propagation of light is called a ray of light.



With time, the wave moves farther giving rise to new wavefronts. All these wavefronts will be concentric spheres of increasing radii as shown in Fig. 9.1 (a). Thus the wave propagates in space by the motion of the wavefronts. The distance between the consecutive wavefronts is one wavelength. It can be seen that as we move away at greater distance from the source, the wavefronts are parts of spheres of very large radii. A limited region taken on such a wavefront can be regarded as a plane wavefront (Fig.9.1b). For example, light from the Sun reaches the Earth with plane wavefronts.

Do You Know?

Small segments of large spherical wavefronts approximate a plane wavefront.

In the study of interference and diffraction, plane waves and plane wavefronts are considered. A usual way to obtain a plane wave is to place a point source of light at the focus of a convex lens. The rays coming out of the lens will constitute plane waves.

9.2 HUYGEN'S PRINCIPLE

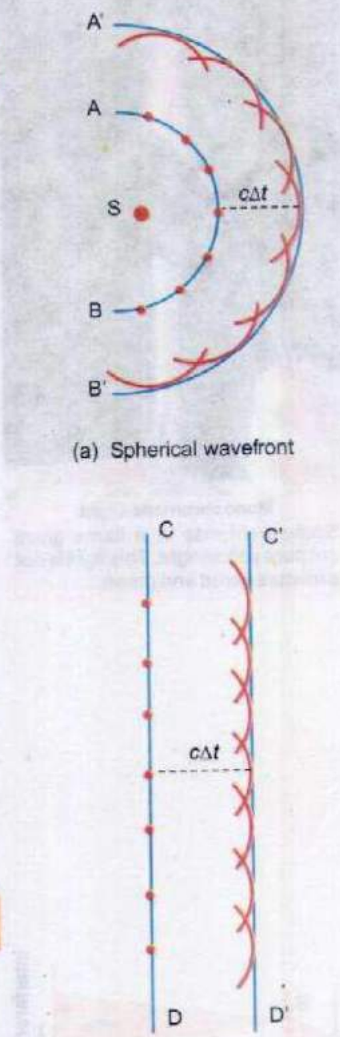
Knowing the shape and location of a wavefront at any instant t, Huygen's principle enables us to determine the shape and location of the new wavefront at a later time $t + \Delta t$. This principle consists of two parts:

(i) Every point of a wavefront may be considered as a source of secondary wavelets which spread out in forward direction with a speed equal to the speed of propagation of the wave.

(ii) The new position of the wavefront after a certain interval of time can be found by constructing a surface that touches all the secondary wavelets.

The principle is illustrated in Fig. 9.2 (a). AB represents the wavefront at any instant t. To determine the wavefront at time $t + \Delta t$, draw secondary wavelets with centre at various points on the wavefront AB and radius as $c\Delta t$ where c is speed of the propagation of the wave as shown in Fig.9.2 (a). The new wavefront at time $t + \Delta t$ is A'B' which is a tangent envelope to all the secondary wavelets.

Figure 9.2 (b) shows a similar construction for a plane wavefront.



(a) Spherical wavefront

(b) Plane wavefront

Fig.9.2

Huygens' construction for determining the position of the wavefronts AB and CD after a time interval Δt. A'B' and C'D' are the new positions of the waveforts.

9.3 INTERFERENCE OF LIGHT WAVES

An oil film floating on water surface exhibits beautiful colour patterns. This happens due to interference of light waves, the phenomenon, which is being discussed in this section.

Conditions for Detectable Interference

It was studied in Chapter 8 that when two waves travel in the same medium, they would interfere constructively or destructively. The amplitude of the resultant wave will be greater then either of the individual waves, if they interfere constructively. In the case of destructive interference, the

For Your Information

Monochromatic Light
Sodium chloride in a flame gives out pure yellow light. This light is not a mixture of red and green.

amplitude of the resultant wave will be less than either of the individual waves.

Interference of light waves is not easy to observe because of the random emission of light from a source. The following conditions must be met, in order to observe the phenomenon.

1. The interfering beams must be monochromatic, that is, of a single wavelength.

2. The interfering beams of light must be coherent.

Consider two or more sources of light waves of the same wavelength. If the sources send out crests or troughs at the same instant, the individual waves maintain a constant phase difference with one another. The monochromatic sources of light which emit waves, having a constant phase difference, are called coherent sources.

A common method of producing two coherent light beams is to use a monochromatic source to illuminate a screen containing two small holes, usually in the shape of slits. The light emerging from the two slits is coherent because a single source produces the original beam and two slits serve only to split it into two parts. The points on a Huygen's wavefront which send out secondary wavelets are also coherent sources of light.

9.4 YOUNG'S DOUBLE SLIT EXPERIMENT

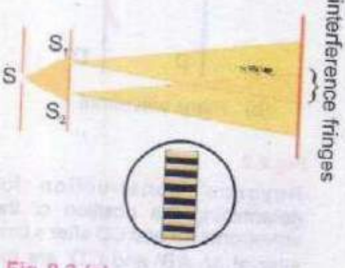


Fig. 9.3 (a)
Ray geometry of Young's double slit experiment.

Fig. 9.3 (a) shows the experimental arrangement, similar to that devised by Young in 1801, for studying interference effects of light. A screen having two narrow slits is illuminated by a beam of monochromatic light. The portion of the wavefront incident on the slits behaves as a source of secondary wavelets (Huygen's principle). The secondary wavelets leaving the slits are coherent. Superposition of these wavelets result in a series of bright and dark bands (fringes) which are observed on a second screen placed at some distance parallel to the first screen.

Let us now consider the formation of bright and dark bands. As pointed out earlier the two slits behave as coherent sources of secondary wavelets. The wavelets arrive at the screen in such a way that at some points crests fall on crests and troughs on troughs resulting in constructive interference and bright fringes are formed. There are some points on the screen where crests meet troughs giving rise to destructive interference and dark fringes are thus formed.

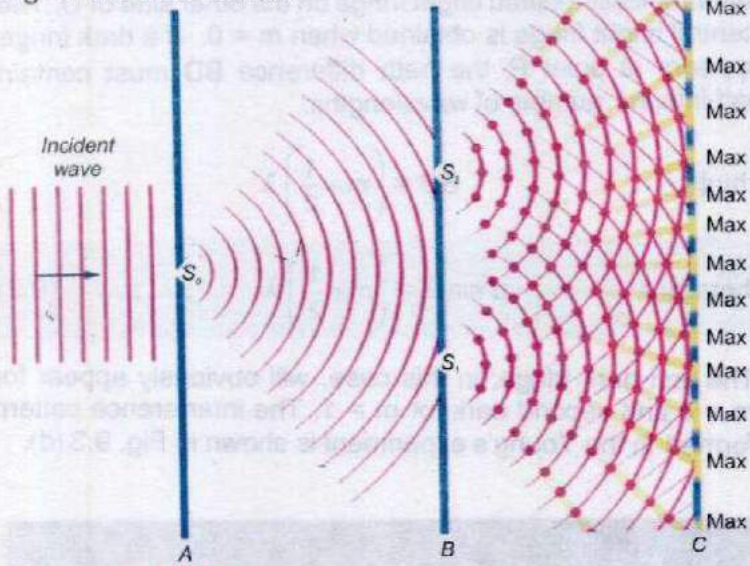


Fig. 9.3 (b)
Young's double slit experiment for interference of light.

The bright fringes are termed as maxima and dark fringes as minima.

In order to derive equations for maxima and minima, an arbitrary point P is taken on the screen on one side of the central point O as shown in Fig. 9.3 (c). AP and BP are the paths of the rays reaching P. The line AD is drawn such that AP = DP. The separation between the centres of the two slits is AB = d. The distance of the screen from the slits is CO = L. The angle between CP and CO is θ. It can be proved that the angle BAD = θ by assuming that AD is nearly normal to BP. The path difference between the wavelets, leaving the slits and arriving at P, is BD. It is the number of wavelengths, contained within BD, that determines whether bright or dark fringe will appear at P. If the point P is to have bright fringe, the path difference BD must be an integral multiple of wavelength.

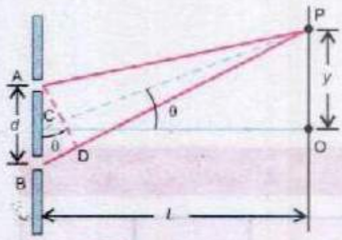


Fig. 9.3 (c)
Geometrical construction of Young's double slit experiment

Thus, BD = mλ, where m = 0, 1, 2,.......

Since BD = d sinθ

therefore $$d \sin\theta = m\lambda \qquad \text{..........} \qquad (9.1)$$

It is observed that each bright fringe on one side of O has symmetrically located bright fringe on the other side of O. The central bright fringe is obtained when m = 0. If a dark fringe appears at point P, the path difference BD must contain half-integral number of wavelengths.

Thus $$BD = \left(m + \frac{1}{2}\right)\lambda$$

therefore $$d \sin\theta = \left(m + \frac{1}{2}\right)\lambda \qquad \text{..........} \qquad (9.2)$$

The first dark fringe, in this case, will obviously appear for m = 0 and second dark for m = 1. The interference pattern formed in the Young's experiment is shown in Fig. 9.3 (d).

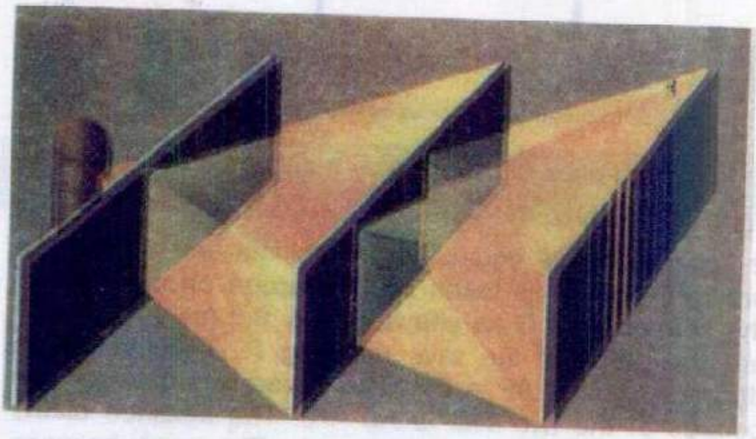


Fig. 9.3 (d)

An interference pattern by monochromatic light in Young's double slits experiment.

For Your Information

θ°	sin θ	tan θ
2	0.035	0.035
4	0.070	0.070
6	0.104	0.105
8	0.139	0.140
10	0.174	0.176

Equations 9.1 and 9.2 can be applied for determining the linear distance on the screen between adjacent bright or dark fringes. If the angle θ is small, then

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

Now from Fig. 9.3 (c), $\tan\theta = y/L$, where y is the distance of the point P from O. If a bright fringe is observed at P, then, from Eq. 9.1, we get,

$$y = m\frac{\lambda L}{d} \quad \text{..........} \quad (9.3)$$

If P is to have dark fringe it can be proved that

$$y = \left(m + \frac{1}{2}\right)\frac{\lambda L}{d} \quad \text{..........} \quad (9.4)$$

In order to determine the distance between two adjacent bright fringes on the screen, mth and (m + 1) th fringes are considered.

For the mth bright fringe, $y_m = m\frac{\lambda L}{d}$

and for the (m + 1)th bright fringe $y_{m+1} = (m+1)\frac{\lambda L}{d}$

If the distance between the adjacent bright fringes is Δy, then

$$\Delta y = y_{m+1} - y_m = (m+1)\frac{\lambda L}{d} - m\frac{\lambda L}{d}$$

Therefore, $$\Delta y = \frac{\lambda L}{d} \quad \text{..........} \quad (9.5)$$

Similarly, the distance between two adjacent dark fringes can be proved to be $\lambda L/d$. It is, therefore, found that the bright and dark fringes are of equal width and are equally spaced.

Eq. 9.5 reveals that fringe spacing increases if red light (long wavelength) is used as compared to blue light (short wavelength). The fringe spacing varies directly with distance L between the slits and screen and inversely with the separation d of the slits.

If the separation d between the two slits, the order m of a bright or dark fringe and fringe spacing Δy are known, the wavelength λ of the light used for interference effect can be determined by applying Eq. 9.5.

Tidbits

An interference pattern formed with white light.

Example 9.1: The distance between the slits in Young's double slit experiment is 0.25 cm. Interference fringes are formed on a screen placed at a distance of 100 cm from the slits. The distance of the third dark fringe from the central bright fringe is 0.059 cm. Find the wavelength of the incident light.

Solution: Given that

$$d = 0.25\,\text{cm} = 2.5 \times 10^{-3}\,\text{m}$$

$$y = 0.059\ \text{cm} = 5.9 \times 10^{-4}\,\text{m}$$

$$L = 100\ \text{cm} = 1\ \text{m}$$

For the 3rd dark fringe m = 2

Using $$y = \left(m + \frac{1}{2}\right)\frac{\lambda L}{d}$$

$$\lambda = \frac{5.9 \times 10^{-4}\ \text{m} \times 2.5 \times 10^{-3}\ \text{m}}{\left(2 + \tfrac{1}{2}\right) \times 1\text{m}}$$

Therefore, $$\lambda = 5.90 \times 10^{-7}\ \text{m} = 590\ \text{nm}$$

Interesting Information

Colours seen on oily water surface are due to interference of incident white light.

Example 9.2: Yellow sodium light of wavelength 589 nm, emitted by a single source passes through two narrow slits 1.00 mm apart. The interference pattern is observed on a screen 225 cm away. How far apart are two adjacent bright fringes?

Solution: Given that

$$\lambda = 589\ \text{nm} = 589 \times 10^{-9}\ \text{m}$$

$$d = 1.00\ \text{mm} = 1.00 \times 10^{-3}\text{m}$$

$$L = 225\ \text{cm} = 2.25\ \text{m}$$

$$\Delta y = ?$$

Using $$\Delta y = \frac{\lambda L}{d}$$

$$\Delta y = \frac{589 \times 10^{-9}\ \text{m} \times 2.25\ \text{m}}{1.0 \times 10^{-3}\ \text{m}}$$

$$\Delta y = 1.33 \times 10^{-3}\text{m} \quad \text{or} \quad 1.33\ \text{mm.}$$

Thus; the adjacent frings will be 1.33 mm apart.

9.5 INTERFERENCE IN THIN FILMS

A thin film is a transparent medium whose thickness is comparable with the wavelength of light. Brilliant and beautiful colours in soap bubbles and oil film on the surface of water are due to interference of light reflected from the two surfaces of the film as explained below:

Consider a thin film of a refracting medium. A beam AB of monochromatic light of wavelength λ is incident on its upper surface. It is partly reflected along BC and partly refracted into the medium along BD. At D it is again partly reflected inside the medium along DE and then at E refracted along EF as shown in Fig. 9.4. The beams BC and EF, being the parts of the same primary beam have a phase coherence. As the film is thin, so the separation between the beams BC and EF will be very small, and they will superpose and the result of their interference will be detected by the eye. It can be seen in Fig. 9.4, that the original beam splits into two parts BC and EF due to the thin film enter the eye after covering different lengths of paths. Their path difference depends upon (i) thickness and nature of the film and (ii) angle of incidence. If the two reflected waves reinforce each other, then the film as seen with the help of a parallel beam of monochromatic light will look bright. However, if the thickness of the film and angle of incidence are such that the two reflected waves cancel each other, the film will look dark.

If white light is incident on a film of irregular thickness at all possible angles, we should consider the interference pattern due to each spectral colour separately. It is quite possible that at a certain place on the film, its thickness and the angle of incidence of light are such that the condition of destructive interference of one colour is being satisfied. Hence, that portion of the film will exhibit the remaining constituent colours of the white light as shown in Fig. 9.5.

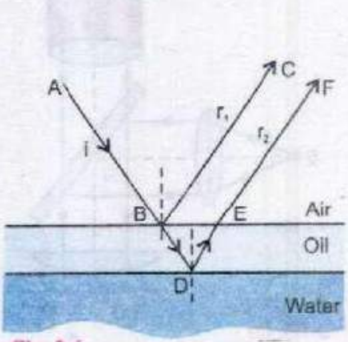


Fig. 9.4
Geometrical construction of interference of light due to a thin oil film.

Do You Know?


The vivid iridescence of peacock feathers due to interference of the light reflected from its complex layered surface.


Fig. 9.5
Interference pattern produced by a thin soap film illuminated by white light.

9.6 NEWTON'S RINGS

When a plano-convex lens of long focal length is placed in contact with a plane glass plate (Fig. 9.6 a), a thin air film is enclosed between the upper surface of the glass plate and the lower surface of the lens. The thickness of the air film is

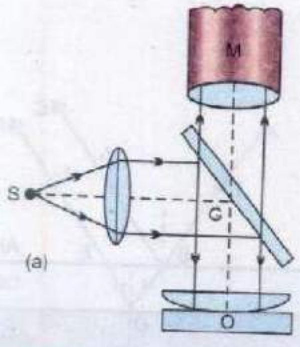


Fig. 9.6 (a)

Experimental arrangement for observing Newton's rings.

almost zero at the point of contact O and it gradually increases as one proceeds towards the periphery of the lens. Thus, the points where the thickness of air film is constant, will lie on a circle with O as centre.

By means of a sheet of glass G, a parallel beam of monochromatic light is reflected towards the plano-convex lens L. Any ray of monochromatic light that strikes the upper surface of the air film nearly along normal is partly reflected and partly refracted. The ray refracted in the air film is also reflected partly at the lower surface of the film. The two reflected rays, i.e. produced at the upper and lower surfaces of the film, are coherent and interfere constructively or destructively. When the light reflected upwards is observed through a microscope M which is focussed on the glass plate, series of dark and bright rings are seen with centre at O (Fig. 9.6 b). These concentric rings are known as Newton's rings.

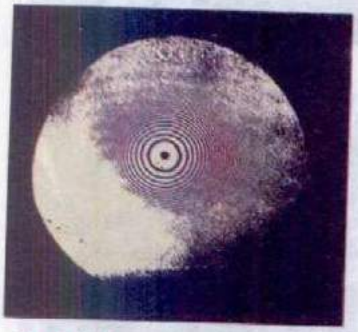


Fig. 9.6 (b)

A pattern of Newton's rings due to interference of monochromatic light.

At the point of contact of the lens and the glass plate, the thickness of the film is effectively zero but due to reflection at the lower surface of air film from denser medium, an additional path difference of $\lambda/2$ is introduced. Consequently, the centre of Newton rings is dark due to destructive interference.

9.7 MICHELSON'S INTERFEROMETER

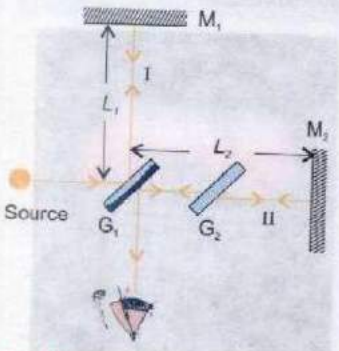


Fig.9.7

Schematic diagram of a Michelson's Interferometer.

Michelson's interferometer is an instrument that can be used to measure distance with extremely high precision. Albert A. Michelson devised this instrument in 1881 using the idea of interference of light rays. The essential features of a Michelson's interferometer are shown schematically in Fig.9.7.

Monochromatic light from an extended source falls on a half silvered glass plate G_1 that partially reflects it and partially transmits it. The reflected portion labelled as I in the figure travels a distance L_1 to mirror M_1, which reflects the beam back towards G_1. The half silvered plate G_1 partially transmits this portion that finally arrives at the observer's eye. The transmitted portion of the original beam labelled as II, travels a distance L_2 to mirror M_2 which reflects the beam back toward G_1. The beam II partially reflected by G_1 also arrives the observer's eye finally. The plate G_2, cut from the same piece of glass as G_1, is introduced in the path of beam II as a compensator plate. G_2, therefore, equalizes the path length of the beams I and II in glass. The two beams having their different paths are coherent. They produce interference effects when they arrive at observer's eyes. The observer then sees a series of parallel interference fringes.

In a practical interferometer, the mirror M_1 can be moved along the direction perpendicular to its surface by means of a precision screw. As the length L_1 is changed, the pattern of interference fringes is observed to shift. If M_1 is displaced through a distance equal to $\lambda/2$, a path difference of double of this displacement is produced, i.e., equal to λ. Thus a fringe is seen shifted forward across the line of reference of cross wire in the eye piece of the telescope used to view the fringes.

A fringe is shifted, each time the mirror is displaced through $\lambda/2$. Hence, by counting the number m of the fringes which are shifted by the displacement L of the mirror, we can write the equation,

$$L = m\,\frac{\lambda}{2} \quad \text{..........} \quad (9.6)$$

Very precise length measurements can be made with an interferometer. The motion of mirror M_1 by only $\lambda/4$ produces a clear difference between brightness and darkness. For $\lambda = 400$ nm, this means a high precision of 100 nm or 10^{-4} mm.

Michelson measured the length of standard metre in terms of the wavelength of red cadmium light and showed that the standard metre was equivalent to 1,553,163.5 wavelengths of this light.

For Your Information

A photograph of Michelson Interferometer.

For Your Information

Interference fringes in the Michelson interferometer.

9.8 DIFFRACTION OF LIGHT

In the interference pattern obtained with Young's double slit experiment (Fig. 9.3 b), the central region of the fringe system is bright. If light travels in a straight line, the central region should appear dark i.e., the shadow of the screen between the two slits. Another simple experiment can be performed for exhibiting the same effect.

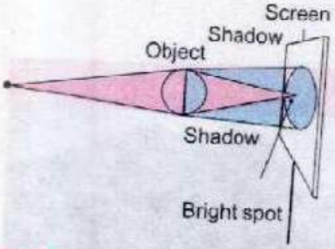


Fig.9.8

Bending of light caused by its passage past a spherical object.

Consider that a small and smooth steel ball of about 3 mm in diameter is illuminated by a point source of light. The shadow of the object is received on a screen as shown in Fig. 9.8 . The shadow of the spherical object is not completely dark but has a bright spot at its centre. According to Huygen's principle, each point on the rim of the sphere behaves as a source of secondary wavelets which illuminate the central region of the shadow.

These two experiments clearly show that when light travels past an obstacle, it does not proceed exactly along a straight path, but bends around the obstacle.

The property of bending of light around obstacles and spreading of light waves into the geometrical shadow of an obstacle is called diffraction.

Point to ponder

Hold two fingers close together to form a slit. Look at a light bulb through the slit. Observe the pattern of light being seen and think why it is so.

The phenomenon is found to be prominent when the wavelength of light is large as compared with the size of the obstacle or aperture of the slit. The diffraction of light occurs, in effect, due to the interference between rays coming from different parts of the same wavefront.

9.9 DIFFRACTION DUE TO A NARROW SLIT

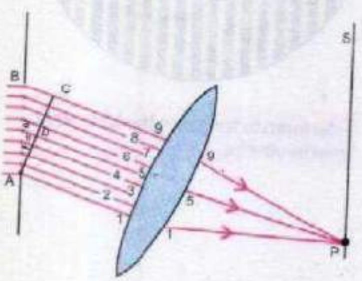


Fig. 9.9

Diffraction of light due to a narrow slit AB. The dots represent the sources of secondary wavelets.

Fig. 9.9 shows the experimental arrangement for studying diffraction of light due to a narrow slit. The slit AB of width d is illuminated by a parallel beam of monochromatic light of wavelength λ. The screen S is placed parallel to the slit for observing the effects of the diffraction of light. A small portion of the incident wavefront passes through the narrow slit. Each point of this section of the wavefront sends out secondary wavelets to the screen. These wavelets then interfere to produce the diffraction pattern. It becomes simple to deal with rays instead of wavefronts as shown in the figure. In this figure, only nine rays have been drawn whereas actually there are a large number of them. Let us consider rays 1 and 5 which are in phase on the wavefront AB.When these reach the wavefront AC, ray 5 would have a path difference ab say equal to $\lambda/2$. Thus, when these two rays reach point P on the screen, they will interfere destructively. Similarly, all other pairs 2 and 6, 3 and 7, 4 and 8 differ in path by $\lambda/2$ and will do the same. For the pairs of rays, the path difference ab= $d/2 \sin\theta$.

The equation for the first minimum is, then

$$\frac{d}{2}\sin\theta = \frac{\lambda}{2}$$

or $$d\sin\theta = \lambda \qquad \text{..........} \qquad (9.7)$$

In general, the conditions for different orders of minima on either side of centre are given by

$$d\sin\theta = m\lambda \quad \text{where } m = \pm(1, 2, 3, \ldots\ldots) \qquad \text{..........} \qquad (9.8)$$

The region between any two consecutive minima both above and below O will be bright. A narrow slit, therefore, produces a series of bright and dark regions with the first bright region at the centre of the pattern. Such a diffraction pattern is shown in Fig. 9.10(a) and (b).

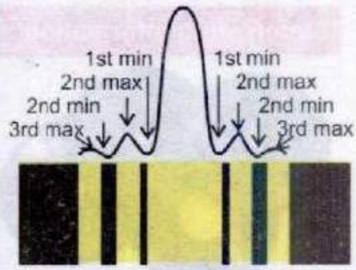


Fig. 9.10 (a)

Diffraction pattern of mono chromatic light produced due to a single slit; graphical representation and photograph of the pattern.

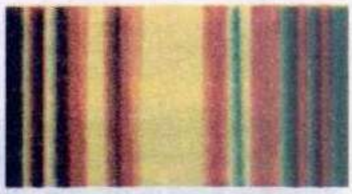


Fig. 9.10 (b)

Diffraction pattern produced by white light through a single slit.

9.10 DIFFRACTION GRATING

A diffraction grating is a glass plate having a large number of close parallel equidistant slits mechanically ruled on it. The transparent spacing between the scratches on the glass plate act as slits. A typical diffraction grating has about 400 to 5000 lines per centimetre.

In order to understand how a grating diffracts light, consider a parallel beam of monochromatic light illuminating the grating at normal incidence (Fig. 9.11). A few of the equally spaced narrow slits are shown in the figure. The distance between two adjacent slits is d, called grating element. Its value is obtained by dividing the length L of the grating by the total number N of the lines ruled on it. The sections of wave-front that pass through the slits behave as sources of secondary wavelets according to Huygen's principle.

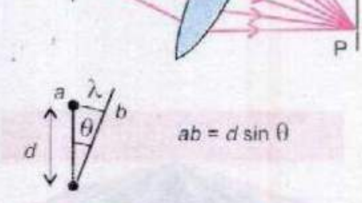


Fig. 9.11

Diffraction of light due to grating

In Fig. 9.11, consider the parallel rays which after diffraction through the grating make an angle θ with AB, the normal to grating. They are then brought to focus on the screen at P by a convex lens. If the path difference between rays 1 and 2 is one wavelength λ, they will reinforce each other at P. As the incident beam consists of parallel rays, the rays from any two consecutive slits will differ in path by λ when they arrive at P. They will, therefore, interfere constructively. Hence, the condition for constructive interference is that ab, the path difference between two consecutive rays, should be equal to λ i.e.,

$$ab = \lambda \qquad \text{..........} \qquad (9.9)$$

From Fig. 9.11

$$ab = d \sin\theta \qquad \text{..........} \qquad (9.10)$$

d being the grating element. Substituting the value of ab in Eq. 9.9

$$d \sin\theta = \lambda \qquad \text{..........} \qquad (9.11)$$

According to Eq. 9.10, when $\theta = 0$ i.e., along the direction of normal to the grating, the path difference between the rays coming out from the slits of the grating will be zero. So we will get a bright image in this direction. This is known as zero order image formed by the grating. If we increase θ on either side of this direction, a value of θ will be arrived at which $d\sin\theta$ will be equal to λ and according to Eq. 9.11, we will again get a bright image. This is known as first order image of the grating. In this way if we continue increasing θ, we will get the second, third, etc. images on either side of the zero order image with dark regions in between. The second, third order bright images would occur according as $d \sin\theta$ becoming equal to 2λ, 3λ, etc. Thus Eq. 9.11 can be written in more general form as

$$d \sin\theta = n\lambda \qquad \text{..........} \qquad (9.12)$$

where $n = 0 \pm 1 \pm 2 \pm 3$ etc.

However, if the incident light contains different wavelengths, the image of each wavelength for a certain value of n is diffracted in a different direction. Thus, separate images are obtained corresponding to each wavelength or colour. Eq. 9.12 shows that the value of θ depends upon n, so the images of different colours are much separated in higher orders.

9.11 DIFFRACTION OF X-RAYS BY CRYSTALS

X-rays is a type of electromagnetic radiation of much shorter wavelength, typically of the order of 10^{-10} m.

Interesting Information

The fine rulings, each 0.5 μ m wide, on a compact disc function as a diffraction grating. When a small source of white light illuminates a disc, the diffracted light forms colored "lanes" that are composite of the diffraction patterns from the rulings.

Can You Tell?

Light waves projected through this diffraction grating produce an interference pattern. What colours are between the bands of interference?

For your Information

Diffraction of white light by a fine diffraction grating

In order to observe the effects of diffraction, the grating spacing must be of the order of the wavelength of the radiation used. The regular array of atoms in a crystal forms a natural diffraction grating with spacing that is typically $\approx 10^{-10}$ m. The scattering of X-rays from the atoms in a crystalline lattice gives rise to diffraction effects very similar to those observed with visible light incident on ordinary grating.

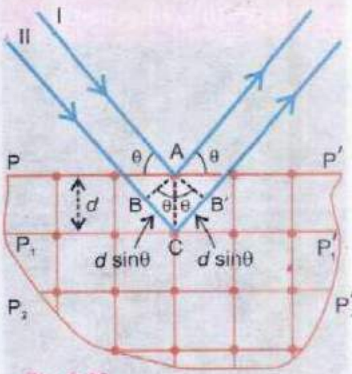


Fig. 9.12

Diffraction of X-rays from the lattice planes of crystal.

The study of atomic structure of crystals by X-rays was initiated in 1914 by W.H. Bragg and W.L Bragg with remarkable achievements. They found that a monochromatic beam of X-rays was reflected from a crystal plane as if it acted like mirror. To understand this effect, a series of atomic planes of constant interplanar spacing d parallel to a crystal face are shown by lines PP′, $P_1P'_1$, $P_2P'_2$, and so on, in Fig. 9.12.

Suppose an X-rays beam is incident at an angle θ on one of the planes. The beam can be reflected from both the upper and the lower planes of atoms. The beam reflected from lower plane travels some extra distance as compared to the beam reflected from the upper plane. The effective path difference between the two reflected beams is $2d\sin\theta$. Therefore, for reinforcement, the path difference should be an integral multiple of the wavelength. Thus

$$2d\sin\theta = n\lambda \quad \ldots\ldots\ldots \quad (9.13)$$

The value of n is referred to as the order of reflection. The equation 9.13 is known as the Bragg equation. It can be used to determine interplanar spacing between similar parallel planes of a crystal if X-rays of known wavelength are allowed to diffract from the crystal.

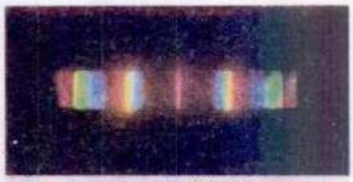
X-ray diffraction has been very useful in determining the structure of biologically important molecules such as haemoglobin, which is an important constituent of blood, and double helix structure of DNA.

Interesting Application

Diffraction of radio waves

Interesting Information

The spectrum of white light due to diffraction grating of 100 slits.

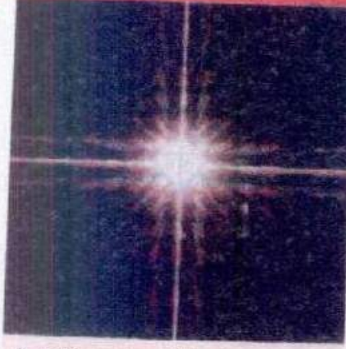


The spectrum of white light due to diffraction grating of 2000 slits.

Example 9.3: Light of wavelength 450 nm is incident on a diffraction grating on which 5000 lines/cm have been ruled.

(i) How many orders of spectra can be observed on either side of the direct beam?

Interesting Illustration



A multi-aperture diffraction pattern. This is a picture of a white-light point source shot through a piece of tightly woven cloth.

Tidbits

Diffraction pattern of a single human hair under laser beam illumination.

For Your Information

Looking through two polarizers. When they are "crossed", very little light passes through.

(ii) Determine the angle corresponding to each order.

Solution: (i) Given that

$$\lambda = 450 \text{ nm} = 450 \times 10^{-9} \text{ m}$$

$$d = \frac{1}{5000} \text{cm} = \frac{1}{500000} \text{ m}$$

For maximum number of order of spectra $\sin\theta = 1$

Since $d \sin\theta = n\lambda$

therefore subsituting the values in the above equation, we get,

$$\frac{1}{500000} \text{ m} \times 1 = n \times 450 \times 10^{-9} \text{ m} \quad \text{or} \quad n = \frac{1}{500000 \times 450 \times 10^{-9}}$$

or $$n = 4.4$$

Hence, the maximum order of spectrum is 4.

(i) For the first order of spectrum, n = 1.

$$d \sin\theta = n\lambda, \quad \text{gives}$$

$$\frac{1}{500000} \text{ m} \times \sin\theta = 1 \times 450 \times 10^{-9} \text{ m}$$

$$\sin\theta = (500000)(450 \times 10^{-9})$$

$$\sin\theta = 0.225 \quad \text{or} \quad \theta = 13^\circ$$

For second order spectrum,n = 2, using Eq. $d\sin\theta = n\lambda$

$$\left(\frac{1}{500000} \text{m}\right) \sin\theta = 2 \times (450 \times 10^{-9} \text{ m})$$

$$\sin\theta = 0.45$$

or $$\theta = 26.7^\circ$$

The third order spectrum (n=3) will be observed at $\theta = 42.5^\circ$

$$\sin\theta = 3 \times 500000 \text{ m}^{-1} \times 450 \times 10^{-9} \text{ m}$$

$$= 0.675 \quad \text{i.e.} \quad \text{at } \theta = 42.5^\circ$$

and the fourth order spectrum (n = 4) will occur at $\theta = 64.2^\circ$

$$\sin\theta = 4 \times 500000 \text{ m}^{-1} \times 450 \times 10^{-9} \text{ m}$$

$$\sin\theta = 0.9 \quad \text{gives} \quad \theta = 64.2^\circ$$

9.12 POLARIZATION

In transverse mechanical waves, such as produced in a stretched string, the vibrations of the particles of the medium are perpendicular to the direction of propagation of the waves. The vibration can be oriented along vertical, horizontal or any other direction (Fig. 9.13). In each of these cases, the transverse mechanical wave is said to be polarized. The plane of polarization is the plane containing the direction of vibration of the particles of the medium and the direction of propagation of the wave.

A light wave produced by oscillating charge consists of a periodic variation of electric field vector accompanied by the magnetic field vector at right angle to each other. Ordinary light has components of vibration in all possible planes. Such a light is unpolarized. On the other hand, if the vibrations are confined only in one plane, the light is said to be polarized.

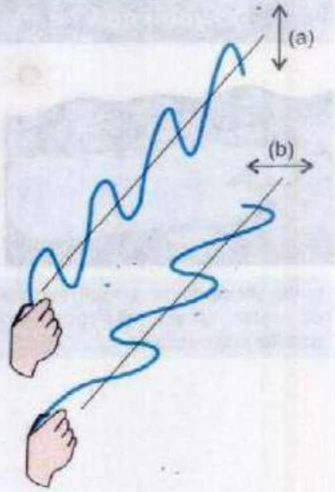


Fig. 9.13
Transverse waves on a string polarized (a) in a vertical plane and (b) in a horizontal plane

Production and Detection of Plane Polarized Light

The light emitted by an ordinary incandescent bulb (and also by the Sun) is unpolarized, because its (electrical) vibrations are randomly oriented in space (Fig. 9.14). It is possible to obtain plane polarized beam of light from un-polarized light by removing all waves from the beam except those having vibrations along one particular direction. This can be achieved by various processes such as selective absorption, reflection from different surfaces, refraction through crystals and scattering by small particles.

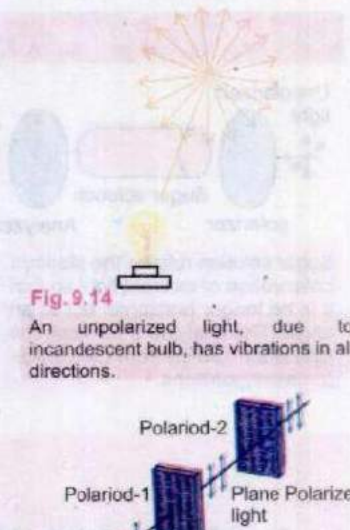


Fig. 9.14
An unpolarized light, due to incandescent bulb, has vibrations in all directions.

The selective absorption method is the most common method to obtain plane polarized light by using certain types of materials called dichroic substances. These materials transmit only those waves, whose vibrations are parallel to a particular direction and will absorb those waves whose vibrations are in other directions. One such commercial polarizing material is a polaroid.

If un-polarized light is made incident on a sheet of polaroid, the transmitted light will be plane polarized. If a second sheet of polaroid is placed in such a way that the axes of the polaroids, shown by straight lines drawn on them, are parallel (Fig. 9.15a), the light is transmitted through the second polaroid also. If the second polaroid is slowly rotated about the beam of light, as axis of rotation, the light emerging out of the second polaroid gets dimmer and dimmer and disappears when the axes become mutually

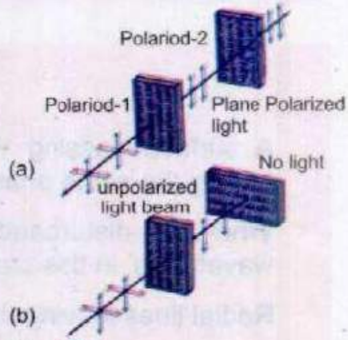
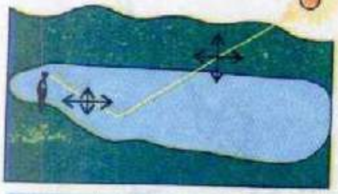


Fig. 9.15
Experimental arrangement to show that light waves are transverse. The lines with arrows indicates electric vibrations of light waves.

Do you know?



Light reflected from smooth surface of water is partially polarized parallel to the surface.

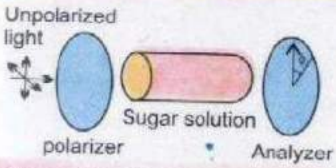
perpendicular (Fig. 9.15 b). The light reappears on further rotation and becomes brightest when the axes are again parallel to each other.

This experiment proves that light waves are transverse waves. If the light waves were longitudinal, they would never disappear even if the two polaroids were mutually perpendicular.

Reflection of light from water, glass, snow and rough road surfaces, for larger angles of incidences, produces glare. Since the reflected light is partially polarized, glare can considerably be reduced by using polaroid sunglasses.

Sunlight also becomes partially polorized because of scattering by air molecules of the Earth's atmosphere. This effect can be observed by looking directly up through a pair of sunglasses made of polarizing glass. At certain orientations of the lenses, less light passes through than at others.

Interesting information



Sugar solution rotates the plane of polarization of incident light so that it is no longer horizontal but at an angle. The analyzer thus stops the light when rotated from the vertical (crossed)positions.

Optical Rotation

When a plane polarized light is passed through certain crystals, they rotate the plane of polarization. Quartz and sodium chlorate crystals are typical examples, which are termed as optically active crystals.

A few millimeter thickness of such crystals will rotate the plane of polarization by many degrees. Certain organic substances, such as sugar and tartaric acid, show optical rotation when they are in solution. This property of optically active substances can be used to determine their concentration in the solutions.

SUMMARY

- A surface passing through all the points undergoing a similar disturbance (i.e., having the same phase) at a given instant is called a wavefront.
- When the disturbance is propagated out in all directions from a point source, the wavefronts in this case are spherical.
- Radial lines leaving the point source in all directions represent rays.
- The distance between two consecutive wavefronts is called wavelength.
- Huygen's principle states that all points on a primary wavefront can be considered as the source of secondary wavelets.

- When two or more waves overlap each other, there is a resultant wave. This phenomenon is called interference.
- Constructive interference occurs when two waves, travelling in the same medium overlap and the amplitude of the resultant wave is greater than either of the individual waves.
- In case of destructive interference, the amplitude of the resulting wave is less than either of the individual waves.
- In Young's double slit experiment,
  (i) for bright fringe, $d \sin\theta = m\lambda$

  (ii) for dark fringe, $d \sin\theta = \left(m + \frac{1}{2}\right)\lambda$

  (iii) the distance between two adjacent bright or dark fringes is

$$\Delta y = \frac{L\lambda}{d}$$

- Newton's rings are circular fringes formed due to interference in a thin air film enclosed between a convex lens and a flat glass plate.
- Michelson's interferometer is used for very precise length measurements. The distance L of the moving mirror when m fringes move in view is $m\lambda/2$.
- Bending of light around obstacles is due to diffraction of light.
- For a diffraction grating:

  $d \sin\theta = n\lambda$ where n stands for nth order of maxima.
- For diffraction of X-rays by crystals

  $2d \sin\theta = n\lambda$ where n is the order of reflection.
- Polarization of light proves that light consists of transverse electromagnetic waves.

QUESTIONS

9.1 Under what conditions two or more sources of light behave as coherent sources?

9.2 How is the distance between interference fringes affected by the separation between the slits of Young's experiment? Can fringes disappear?

9.3 Can visible light produce interference fringes? Explain.

9.4 In the Young's experiment, one of the slits is covered with blue filter and other with red filter. What would be the pattern of light intensity on the screen?

9.5 Explain whether the Young's experiment is an experiment for studying interference or diffraction effects of light.

9.6 An oil film spreading over a wet footpath shows colours. Explain how does it happen?

9.7 Could you obtain Newton's rings with transmitted light? If yes, would the pattern be different from that obtained with reflected light?

9.8 In the white light spectrum obtained with a diffraction grating, the third order image of a wavelength coincides with the fourth order image of a second wavelength. Calculate the ratio of the two wavelengths.

9.9 How would you manage to get more orders of spectra using a diffraction grating?

9.10 Why the polaroid sunglasses are better than ordinary sunglasses?

9.11 How would you distinguish between un-polarized and plane-polarized lights?

9.12 Fill in the blanks.

(i) According to ________ principle, each point on a wavefront acts as a source of secondary ________.

(ii) In Young's experiment, the distance between two adjacent bright fringes for violet light is ________ than that for green light.

(iii) The distance between bright fringes in the interference pattern ________ as the wavelength of light used increases.

(iv) A diffraction grating is used to make a diffraction pattern for yellow light and then for red light. The distances between the red spots will be ________ than that for yellow light.

(v) The phenomenon of polarization of light reveals that light waves are ________ waves.

(vi) A polaroid is a commercial ________.

(vii) A polaroid glass ________ glare of light produced at a road surface.

NUMERICAL PROBLEMS

9.1 Light of wavelength 546 nm is allowed to illuminate the slits of Young's experiment. The separation between the slits is 0.10 mm and the distance of the screen from the slits where interference effects are observed is 20 cm. At what angle the first minimum will fall? What will be the linear distance on the screen between adjacent maxima?

(Ans: 0.16°, 1.1 mm)

9.2 Calculate the wavelength of light, which illuminates two slits 0.5 mm apart and produces an interference pattern on a screen placed 200 cm away from the slits. The first bright fringe is observed at a distance of 2.40 mm from the central bright image.

(Ans: 600 nm)

9.3 In a double slit experiment the second order maximum occurs at $\theta = 0.25^{\circ}$. The wavelength is 650 nm. Determine the slit separation.

(Ans: 0.30 mm)

9.4 A monochromatic light of $\lambda = 588$ nm is allowed to fall on the half silvered glass plate G_1, in the Michelson Interferometer. If mirror M_1 is moved through 0.233 mm, how many fringes will be observed to shift?

(Ans: 792)

9.5 A second order spectrum is formed at an angle of 38.0° when light falls normally on a diffraction grating having 5400 lines per centimetre. Determine wavelength of the light used.

(Ans. 570 nm)

9.6 A light is incident normally on a grating which has 2500 lines per centimetre. Compute the wavelength of a spectral line for which the deviation in second order is 15.0°.

(Ans: 518 nm)

9.7 Sodium light ($\lambda = 589$ nm) is incident normally on a grating having 3000 lines per centimetre. What is the highest order of the spectrum obtained with this grating?

(Ans: 5th)

9.8 Blue light of wavelength 480 nm illuminates a diffraction grating. The second order image is formed at an angle of 30° from the central image. How many lines in a centimetre of the grating have been ruled?

(Ans: 5.2×10^3 lines per cm)

9.9 X-rays of wavelength 0.150 nm are observed to undergo a first order reflection at a Bragg angle of 13.3° from a quartz (SiO_2) crystal. What is the interplanar spacing of the reflecting planes in the crystal?

(Ans: 0.326 nm)

9.10 An X-ray beam of wavelength λ undergoes a first order reflection from a crystal when its angle of incidence to a crystal face is 26.5°, and an X-ray beam of wavelength 0.097 nm undergoes a third order reflection when its angle of incidence to that face is 60.0°. Assuming that the two beams reflect from the same family of planes, calculate **(a)** the interplanar spacing of the planes and **(b)** the wavelength λ.

[Ans: **(a)** 0.168 nm **(b)** 0.150 nm]