Does light travel in a straight line?

Light travels in a straight line in Class VI; it does not do so in Class XII and beyond! Surprised, aren't you?

In school, you are shown an experiment in which you take three cardboards with pinholes in them, place a candle on one side and look from the other side. If the flame of the candle and the three pinholes are in a straight line, you can see the candle. Even if one of them is displaced a little, you cannot see the candle. *This proves*, so your teacher says, *that light travels in a straight line*.

In the present book, there are two consecutive chapters, one on ray optics and the other on wave optics. Ray optics is based on rectilinear propagation of light, and deals with mirrors, lenses, reflection, refraction, etc. Then you come to the chapter on wave optics, and you are told that light travels as a wave, that it can bend around objects, it can diffract and interfere, etc.

In optical region, light has a wavelength of about half a micrometre. If it encounters an obstacle of about this size, it can bend around it and can be seen on the other side. Thus a micrometre size obstacle will not be able to stop a light ray. If the obstacle is much larger, however, light will not be able to bend to that extent, and will not be seen on the other side.

This is a property of a wave in general, and can be seen in sound waves too. The sound wave of our speech has a wavelength of about 50 cm to 1 m. If it meets an obstacle of the size of a few metres, it bends around it and reaches points behind the obstacle. But when it comes across a larger obstacle of a few hundred metres, such as a hillock, most of it is reflected and is heard as an echo.

Then what about the primary school experiment? What happens there is that when we move any cardboard, the displacement is of the order of a few millimetres, which is much larger than the wavelength of light. Hence the candle cannot be seen. If we are able to move one of the cardboards by a micrometer or less, light will be able to diffract, and the candle will still be seen.

One could add to the first sentence in this box: *It learns how to bend as it grows up*!

10.2 Huygens Principle

We would first define a wavefront: when we drop a small stone on a calm pool of water, waves spread out from the point of impact. Every point on the surface starts oscillating with time. At any instant, a photograph of the surface would show circular rings on which the disturbance is maximum. Clearly, all points on such a circle are oscillating in phase because they are at the same distance from the source. Such a locus of points, which oscillate in phase is called a *wavefront*; thus *a wavefront is defined as a surface of constant phase*. The speed with which the wavefront moves outwards from the source is called the speed of the wave. The energy of the wave travels in a direction perpendicular to the wavefront.

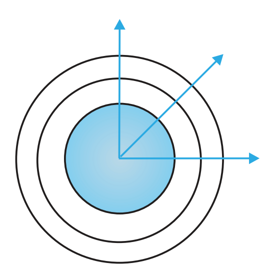


FIGURE 10.1 (a) A diverging spherical wave emanating from a point source. The wavefronts are spherical.

If we have a point source emitting waves uniformly in all directions, then the locus of points which have the same amplitude and vibrate in the same phase are spheres and we have what is known as a *spherical wave* as shown in Fig. 10.1(a). At a large distance from the source, a

EXAMPLE 10.2

oscillators, which take up the frequency of the external agency (light) causing forced oscillations. The frequency of light emitted by a charged oscillator equals its frequency of oscillation. Thus, the frequency of scattered light equals the frequency of incident light.

(b) No. Energy carried by a wave depends on the amplitude of the wave, not on the speed of wave propagation.

(c) For a given frequency, intensity of light in the photon picture is determined by the number of photons crossing an unit area per unit time.

10.4 COHERENT AND INCOHERENT ADDITION OF WAVES

In this section we will discuss the interference pattern produced by the superposition of two waves. You may recall that we had discussed the superposition principle in Chapter 15 of your Class XI textbook. Indeed the entire field of interference is based on the *superposition principle* according to which *at a particular point in the medium, the resultant displacement produced by a number of waves is the vector sum of the displacements produced by each of the waves*.

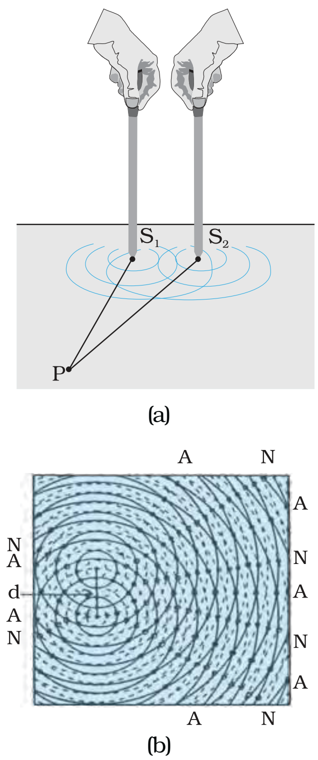


FIGURE 10.8 (a) Two needles oscillating in phase in water represent two coherent sources. (b) The pattern of displacement of water molecules at an instant on the surface of water showing nodal N (no displacement) and antinodal A (maximum displacement) lines.

Consider two needles S_1 and S_2 moving periodically up and down in an identical fashion in a trough of water [Fig. 10.8(a)]. They produce two water waves, and at a particular point, the phase difference between the displacements produced by each of the waves does not change with time; when this happens the two sources are said to be *coherent*. Figure 10.8(b) shows the position of crests (solid circles) and troughs (dashed circles) at a given instant of time. Consider a point P for which

$$S_1 P = S_2 P$$

Since the distances S_1 P and S_2 P are equal, waves from S_1 and S_2 will take the same time to travel to the point P and waves that emanate from S_1 and S_2 in phase will also arrive, at the point P, in phase.

Thus, if the displacement produced by the source S_1 at the point P is given by

$$y_1 = a \cos \omega t$$

then, the displacement produced by the source S_2 (at the point P) will also be given by

$$y_2 = a \cos \omega t$$

Thus, the resultant of displacement at P would be given by

$$y = y_1 + y_2 = 2\, a \cos \omega t$$

Since the intensity is the proportional to the square of the amplitude, the resultant intensity will be given by

$$I = 4\, I_0$$

where I_0 represents the intensity produced by each one of the individual sources; I_0 is proportional to a^2. In fact at any point on the perpendicular bisector of S_1S_2, the intensity will be $4I_0$. The two sources are said to interfere constructively and we have what is referred to as *constructive interference*. We next consider a point *Q* [Fig. 10.9(a)] for which

$S_2Q - S_1Q = 2\lambda$

The waves emanating from S_1 will arrive exactly two cycles earlier than the waves from S_2 and will again be in phase [Fig. 10.9(a)]. Thus, if the displacement produced by S_1 is given by

$y_1 = a \cos \omega t$

then the displacement produced by S_2 will be given by

$y_2 = a \cos (\omega t - 4\pi) = a \cos \omega t$

where we have used the fact that a path difference of 2λ corresponds to a phase difference of 4π. The two displacements are once again in phase and the intensity will again be $4\,I_0$ giving rise to constructive interference. In the above analysis we have assumed that the distances S_1Q and S_2Q are much greater than *d* (which represents the distance between S_1 and S_2) so that although S_1Q and S_2Q are not equal, the amplitudes of the displacement produced by each wave are very nearly the same.

We next consider a point R [Fig. 10.9(b)] for which

$S_2R - S_1R = -2.5\lambda$

The waves emanating from S_1 will arrive exactly two and a half cycles later than the waves from S_2 [Fig. 10.10(b)]. Thus if the displacement produced by S_1 is given by

$y_1 = a \cos \omega t$

then the displacement produced by S_2 will be given by

$y_2 = a \cos (\omega t + 5\pi) = - a \cos \omega t$

where we have used the fact that a path difference of 2.5λ corresponds to a phase difference of 5π. The two displacements are now out of phase and the two displacements will cancel out to give zero intensity. This is referred to as *destructive interference*.

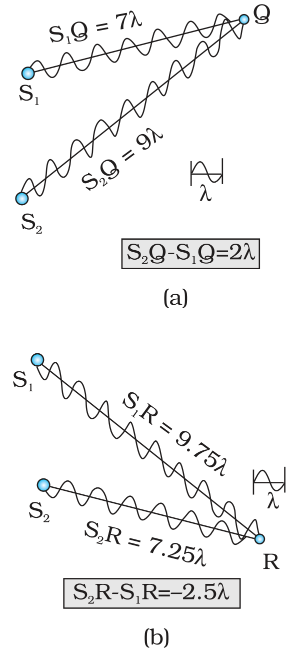


FIGURE 10.9 (a) Constructive interference at a point Q for which the path difference is 2λ. (b) Destructive interference at a point R for which the path difference is $2.5\,\lambda$.

To summarise: If we have two coherent sources S_1 and S_2 vibrating in phase, then for an arbitrary point P whenever the path difference,

$$S_1P \sim S_2P = n\lambda \quad (n = 0, 1, 2, 3,...) \tag{10.10}$$

we will have constructive interference and the resultant intensity will be $4I_0$; the sign ~ between S_1P and S_2P represents the difference between S_1P and S_2P. On the other hand, if the point P is such that the path difference,

$$S_1P \sim S_2P = (n+\frac{1}{2})\,\lambda \quad (n = 0, 1, 2, 3, ...) \tag{10.11}$$

we will have *destructive interference* and the resultant intensity will be zero. Now, for any other arbitrary point G (Fig. 10.10) let the phase difference between the two displacements be ϕ. Thus, if the displacement produced by S_1 is given by

$y_1 = a \cos \omega t$

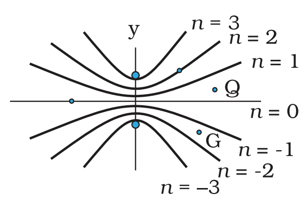


FIGURE 10.10 Locus of points for which $S_1P - S_2P$ is equal to zero, $\pm\lambda$, $\pm 2\lambda$, $\pm 3\lambda$.

then, the displacement produced by S_2 would be

$$y_2 = a \cos(\omega t + \phi)$$

and the resultant displacement will be given by

$$y = y_1 + y_2$$

$$= a\,[\cos \omega t + \cos(\omega t + \phi)]$$

$$= 2\,a \cos(\phi/2) \cos(\omega t + \phi/2)$$

The amplitude of the resultant displacement is $2a \cos(\phi/2)$ and therefore the intensity at that point will be

$$I = 4\,I_0 \cos^2(\phi/2) \qquad (10.12)$$

If $\phi = 0, \pm 2\pi, \pm 4\pi, \ldots$ which corresponds to the condition given by Eq. (10.10) we will have constructive interference leading to maximum intensity. On the other hand, if $\phi = \pm\pi, \pm 3\pi, \pm 5\pi \ldots$ [which corresponds to the condition given by Eq. (10.11)] we will have destructive interference leading to zero intensity.

Now if the two sources are coherent (i.e., if the two needles are going up and down regularly) then the phase difference ϕ at any point will not change with time and we will have a stable interference pattern; i.e., the positions of maxima and minima will not change with time. However, if the two needles do not maintain a constant phase difference, then the interference pattern will also change with time and, if the phase difference changes very rapidly with time, the positions of maxima and minima will also vary rapidly with time and we will see a "time-averaged" intensity distribution. When this happens, we will observe an average intensity that will be given by

$$< I >= 4I_0 < \cos^2(\phi/2) > \qquad (10.13)$$

where angular brackets represent time averaging. Indeed it is shown in Section 7.2 that if $\phi(t)$ varies randomly with time, the time-averaged quantity $< \cos^2(\phi/2) >$ will be 1/2. This is also intuitively obvious because the function $\cos^2(\phi/2)$ will randomly vary between 0 and 1 and the average value will be 1/2. The resultant intensity will be given by

$$I = 2\,I_0 \qquad (10.14)$$

at all points.

When the phase difference between the two vibrating sources changes rapidly with time, we say that the two sources are incoherent and when this happens the intensities just add up. This is indeed what happens when two separate light sources illuminate a wall.

Ripple Tank experiments on wave interference
http://www.colorado.edu/physics/2000/applets/fourier.html

PHYSICS

10.5 Interference of Light Waves and Young's Experiment

We will now discuss interference using light waves. If we use two sodium lamps illuminating two pinholes (Fig. 10.11) we will not observe any interference fringes. This is because of the fact that the light wave emitted from an ordinary source (like a sodium lamp) undergoes abrupt phase changes in times of the order of 10^{-10} seconds. Thus the light waves coming out from two independent sources of light will not have any fixed phase relationship and would be incoherent, when this happens, as discussed in the previous section, the intensities on the screen will add up.

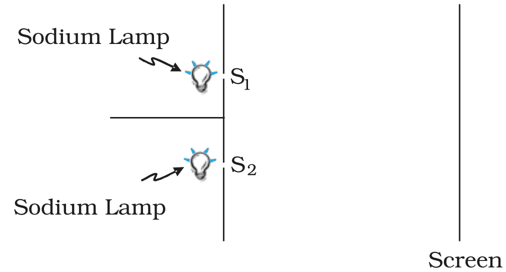
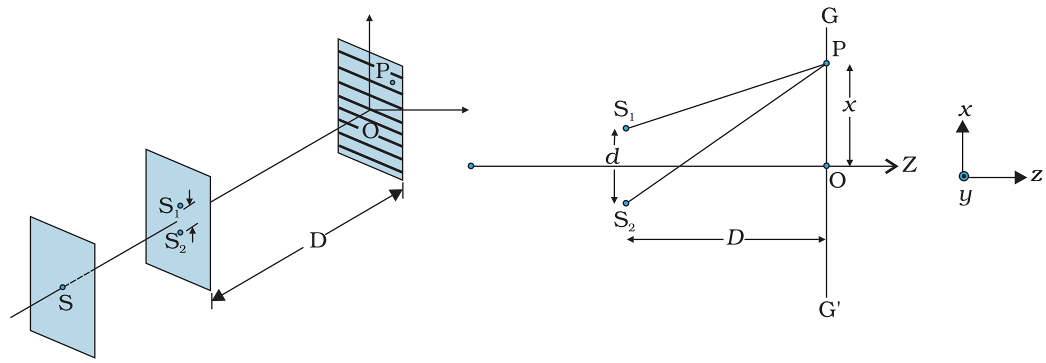


FIGURE 10.11 If two sodium lamps illuminate two pinholes S_1 and S_2, the intensities will add up and no interference fringes will be observed on the screen.

The British physicist Thomas Young used an ingenious technique to "lock" the phases of the waves emanating from S_1 and S_2. He made two pinholes S_1 and S_2 (very close to each other) on an opaque screen [Fig. 10.12(a)]. These were illuminated by another pinholes that was in turn, lit by a bright source. Light waves spread out from S and fall on both S_1 and S_2. S_1 and S_2 then behave like two coherent sources because light waves coming out from S_1 and S_2 are derived from the same original source and any abrupt phase change in S will manifest in exactly similar phase changes in the light coming out from S_1 and S_2. Thus, the two sources S_1 and S_2 will be *locked* in phase; i.e., they will be coherent like the two vibrating needle in our water wave example [Fig. 10.8(a)].



(a) (b)

FIGURE 10.12 Young's arrangement to produce interference pattern.

Thus spherical waves emanating from S_1 and S_2 will produce interference fringes on the screen GG′, as shown in Fig. 10.12(b). The positions of maximum and minimum intensities can be calculated by using the analysis given in Section 10.4 where we had shown that for an arbitrary point P on the line GG′ [Fig. 10.12(b)] to correspond to a maximum, we must have

$$S_2P - S_1P = n\lambda; \quad n = 0, 1, 2 \ldots \tag{10.15}$$

Now,

$$(S_2P)^2 - (S_1P)^2 = \left[D^2 + \left(x + \frac{d}{2}\right)^2\right] - \left[D^2 + \left(x - \frac{d}{2}\right)^2\right] = 2x\,d$$

THOMAS YOUNG (1773 – 1829)

Thomas Young (1773 – 1829) English physicist, physician and Egyptologist. Young worked on a wide variety of scientific problems, ranging from the structure of the eye and the mechanism of vision to the decipherment of the Rosetta stone. He revived the wave theory of light and recognised that interference phenomena provide proof of the wave properties of light.

where $S_1S_2 = d$ and $OP = x$. Thus

$$S_2P - S_1P = \frac{2xd}{S_2P + S_1P} \tag{10.16}$$

If x, $d \ll D$ then negligible error will be introduced if $S_2P + S_1P$ (in the denominator) is replaced by $2D$. For example, for $d = 0.1$ cm, $D = 100$ cm, OP = 1 cm (which correspond to typical values for an interference experiment using light waves), we have

$$S_2P + S_1P = [(100)^2 + (1.05)^2]^{½} + [(100)^2 + (0.95)^2]^{½}$$

$$\approx 200.01 \text{ cm}$$

Thus if we replace $S_2P + S_1P$ by $2D$, the error involved is about 0.005%. In this approximation, Eq. (10.16) becomes

$$S_2P - S_1P \approx \tag{10.17}$$

Hence we will have constructive interference resulting in a bright region when

$$x = x_n = \frac{n\lambda D}{d}; \; n = 0, \pm 1, \pm 2, \ldots \tag{10.18}$$

On the other hand, we will have a dark region near

$$x = x_n = (n + \quad) \frac{\lambda D}{d}; \quad n = 0, \pm 1, \pm 2 \tag{10.19}$$

Thus dark and bright bands appear on the screen, as shown in Fig. 10.13. Such bands are called *fringes*. Equations (10.18) and (10.19) show that dark and bright fringes are equally spaced and the distance between two consecutive bright and dark fringes is given by

$$\beta = x_{n+1} - x_n$$

$$\text{or} \quad \beta = \frac{\lambda D}{d} \tag{10.20}$$

which is the expression for the *fringe width*. Obviously, the central point O (in Fig. 10.12) will be bright because $S_1O = S_2O$ and it will correspond to $n = 0$. If we consider the line perpendicular to the plane of the paper and passing through O [i.e., along the y-axis] then all points on this line will be equidistant from S_1 and S_2 and we will have a bright central fringe which is a straight line as shown in Fig. 10.13. In order to determine the shape of the interference pattern on the screen we note that a particular fringe would correspond to the locus of points with a constant value of $S_2P - S_1P$. Whenever this constant is an integral multiple of λ, the fringe will be bright and whenever it is an odd integral multiple of $\lambda/2$ it will be a dark fringe. Now, the locus of the point P lying in the x-y plane such that $S_2P - S_1P$ ($= \Delta$) is a constant, is a hyperbola. Thus the fringe pattern will strictly be a hyperbola; however, if the distance D is very large compared to the fringe width, the fringes will be very nearly straight lines as shown in Fig. 10.13.

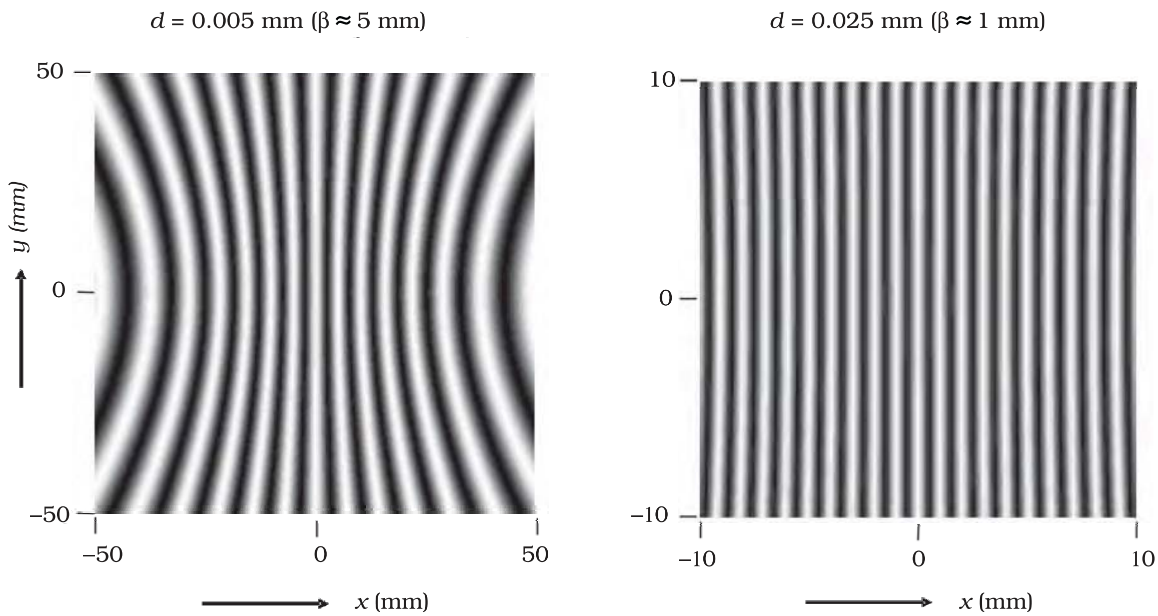


FIGURE 10.13 Computer generated fringe pattern produced by two point source S_1 and S_2 on the screen GG′ (Fig. 10.12); (a) and (b) correspond to d = 0.005 mm and 0.025 mm, respectively (both figures correspond to D = 5 cm and $\lambda = 5 \times 10^{-5}$ cm.) (Adopted from OPTICS by A. Ghatak, Tata McGraw Hill Publishing Co. Ltd., New Delhi, 2000.)

In the double-slit experiment shown in Fig. 10.12, we have taken the source hole S on the perpendicular bisector of the two slits, which is shown as the line SO. What happens if the source S is slightly away from the perpendicular bisector. Consider that the source is moved to some new point S′ and suppose that Q is the mid-point of S_1 and S_2. If the angle S′QS is ϕ, then the central bright fringe occurs at an angle $-\phi$, on the other side. Thus, if the source S is on the perpendicular bisector, then the central fringe occurs at O, also on the perpendicular bisector. If S is shifted by an angle ϕ to point S′, then the central fringe appears at a point *O′* at an angle $-\phi$, which means that it is shifted by the same angle on the other side of the bisector. This also means that the source S′, the mid-point Q and the point O′ of the central fringe are in a straight line.

We end this section by quoting from the Nobel lecture of Dennis Gabor*

The wave nature of light was demonstrated convincingly for the first time in 1801 by Thomas Young by a wonderfully simple experiment. He let a ray of sunlight into a dark room, placed a dark screen in front of it, pierced with two small pinholes, and beyond this, at some distance, a white screen. He then saw two darkish lines at both sides of a bright line, which gave him sufficient encouragement to repeat the experiment, this time with spirit flame as light source, with a little salt in it to produce the bright yellow sodium light. This time he saw a number of dark lines, regularly spaced; the first clear proof that light added to light can produce darkness. This phenomenon is called

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* Dennis Gabor received the 1971 Nobel Prize in Physics for discovering the principles of holography.

interference. Thomas Young had expected it because he believed in the wave theory of light.

We should mention here that the fringes are straight lines although S_1 and S_2 are point sources. If we had slits instead of the point sources (Fig. 10.14), each pair of points would have produced straight line fringes resulting in straight line fringes with increased intensities.

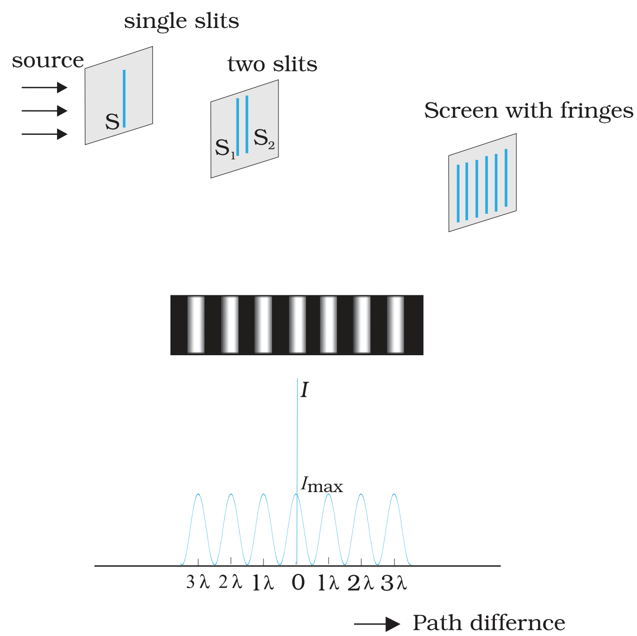

FIGURE 10.14 Photograph and the graph of the intensity distribution in Young's double-slit experiment.

Interactive animation of Young's experiment
http://vsg.quasihome.com/interfer.html

EXAMPLE 10.3

Example 10.3 Two slits are made one millimetre apart and the screen is placed one metre away. What is the fringe separation when blue-green light of wavelength 500 nm is used?

Solution Fringe spacing $= \dfrac{D\lambda}{d} = \dfrac{1 \times 5 \times 10^{-7}}{1 \times 10^{-3}}$ m

$= 5 \times 10^{-4}$ m = 0.5 mm

EXAMPLE 10.4

Example 10.4 What is the effect on the interference fringes in a Young's double-slit experiment due to each of the following operations:

(a) the screen is moved away from the plane of the slits;

(b) the (monochromatic) source is replaced by another (monochromatic) source of shorter wavelength;

(c) the separation between the two slits is increased;

(d) the source slit is moved closer to the double-slit plane;

(e) the width of the source slit is increased;

(f) the monochromatic source is replaced by a source of white light?

(In each operation, take all parameters, other than the one specified, to remain unchanged.)

Solution

(a) Angular separation of the fringes remains constant ($= \lambda/d$). The actual separation of the fringes increases in proportion to the distance of the screen from the plane of the two slits.

(b) The separation of the fringes (and also angular separation) decreases. See, however, the condition mentioned in (d) below.

(c) The separation of the fringes (and also angular separation) decreases. See, however, the condition mentioned in (d) below.

(d) Let s be the size of the source and S its distance from the plane of the two slits. For interference fringes to be seen, the condition $s/S < \lambda/d$ should be satisfied; otherwise, interference patterns produced by different parts of the source overlap and no fringes are seen. Thus, as S decreases (i.e., the source slit is brought closer), the interference pattern gets less and less sharp, and when the source is brought too close for this condition to be valid, the fringes disappear. Till this happens, the fringe separation remains fixed.

(e) Same as in (d). As the source slit width increases, fringe pattern gets less and less sharp. When the source slit is so wide that the condition $s/S \le \lambda/d$ is not satisfied, the interference pattern disappears.

(f) The interference patterns due to different component colours of white light overlap (incoherently). The central bright fringes for different colours are at the same position. Therefore, the central fringe is white. For a point P for which $S_2P - S_1P = \lambda_b/2$, where λ_b ($\approx$ 4000 Å) represents the wavelength for the blue colour, the blue component will be absent and the fringe will appear red in colour. Slightly farther away where $S_2Q - S_1Q = \lambda_b = \lambda_r/2$ where λ_r ($\approx$ 8000 Å) is the wavelength for the red colour, the fringe will be predominantly blue.

Thus, the fringe closest on either side of the central white fringe is red and the farthest will appear blue. After a few fringes, no clear fringe pattern is seen.

EXAMPLE 10.4

10.6 DIFFRACTION

If we look clearly at the shadow cast by an opaque object, close to the region of geometrical shadow, there are alternate dark and bright regions just like in interference. This happens due to the phenomenon of diffraction. Diffraction is a general characteristic exhibited by all types of waves, be it sound waves, light waves, water waves or matter waves. Since the wavelength of light is much smaller than the dimensions of most obstacles; we do not encounter diffraction effects of light in everyday observations. However, the finite resolution of our eye or of optical