The subject of the previous chapter depends on the particle nature of light. Wave optics depends on the wave nature of light. The three primary topics we examine in this chapter are interference, diffraction, and polarization. These phenomena can't be adequately explained with ray optics, but can be understood if light is viewed as a wave.

2.1 Interference:

The two waves could add together either constructively or destructively. In constructive interference, the amplitude of the resultant wave is greater than that of either of the individual waves, whereas in destructive interference, the resultant amplitude is less than that of either individual wave. Light waves also interfere with each other. Fundamentally, all interference associated with light waves arises when the electromagnetic fields that constitute the individual waves combine. Interference effects in light waves aren't easy to observe because of the short wavelengths involved (about $4 * 10^{-7}$ m to about $7 * 10^{-7}$ m). For sustained interference between two sources of light to be observed, the following conditions must be met:

1. The sources must be **coherent**, which means the waves they emit must maintain a constant phase with respect to each other.

2. The waves must have identical wavelengths.

At certain points, the two waves may be in phase. The amplitude of the resultant wave will then be equal to the sum of the amplitudes of the two waves, as shown figure (1).

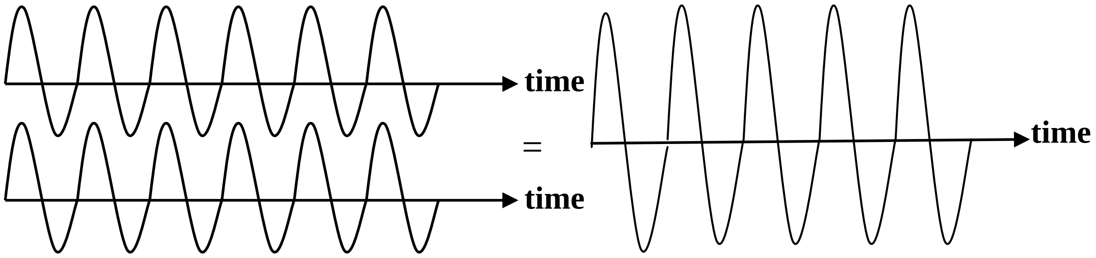


Figure (1)

Thus, the amplitude of resultant wave

$A_R = A+A = 2A.$ (2.1)

Hence, the intensity of the resultant wave

$I_R \propto A_R^2 = 2^2A^2 = 2^2I.$ (2.2)

It is obvious that the resultant intensity is greater than the sum of intensities due to individual waves.

$I_R > I + I = 2I$ (2.3)

Therefore, the interference produced at these points is known as ***constructive interference.*** A stationary bright band of light is observed at points constructive interference

. At certain other points, the two waves may be in opposite phase. The amplitude of the resultant wave will then be equal to the sum of the amplitudes of the two waves, as shown figure (2).

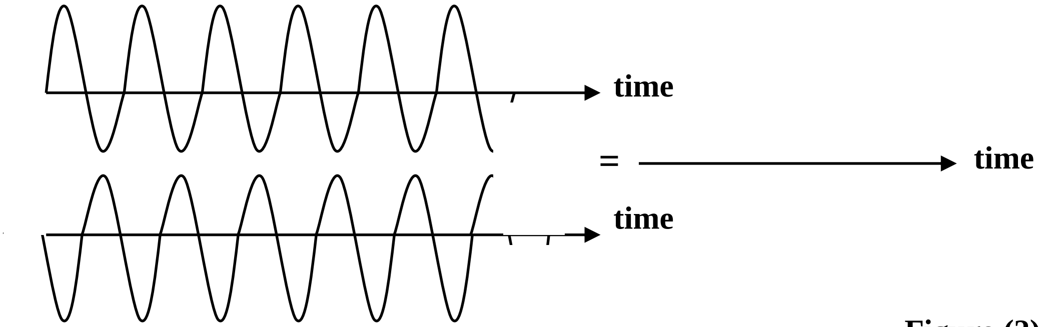


Figure (2)

Thus, the amplitude of resultant wave

$$A_R = A - A = 0. \tag{2.4}$$

Hence, the intensity of the resultant wave

$$I_R \propto 0^2 = 0. \tag{2.5}$$

It is obvious that the resultant intensity is less than the sum of intensities due to individual waves.

$$I_R < 2I \tag{2.6}$$

Therefore, the interference produced at these points is known as ***destructive interference.*** A stationary dark band of light is observed at points destructive interference.

$$\Delta = m\lambda \qquad \boldsymbol{constructive\ interference} \tag{2.7}$$

$$\Delta = (2m + 1)\frac{\lambda}{2} \qquad \boldsymbol{destructive\ interference} \tag{2.8}$$

Where m=0, 1,2,3,……………….. and Δ optical path difference.

The phenomenon of redistribution of light energy due to the superposition of light waves from two or more coherent sources is known as interference.

2.1.2 Young's Double-Slit Experiment-Wave front Division

A common method for producing two coherent light sources is to use a monochromatic source to illuminate a barrier containing two small openings (usually in the shape of slits). The light emerging from the two slits is coherent because a single source produces the original light beam and the two slits serve only to separate the original beam into two parts.

Any random change in the light emitted by the source occurs in both beams at the same time, and as a result interference effects can be observed when the light from the two slits arrives at a viewing screen. If the light traveled only in its original direction after passing through the slits, as shown in Figure 3a, the waves would not overlap and no interference pattern would be seen. The waves spread out from the slits as shown in Figure 3b. In other words, the light deviates from a straight-line path and enters the region that would otherwise be shadowed.

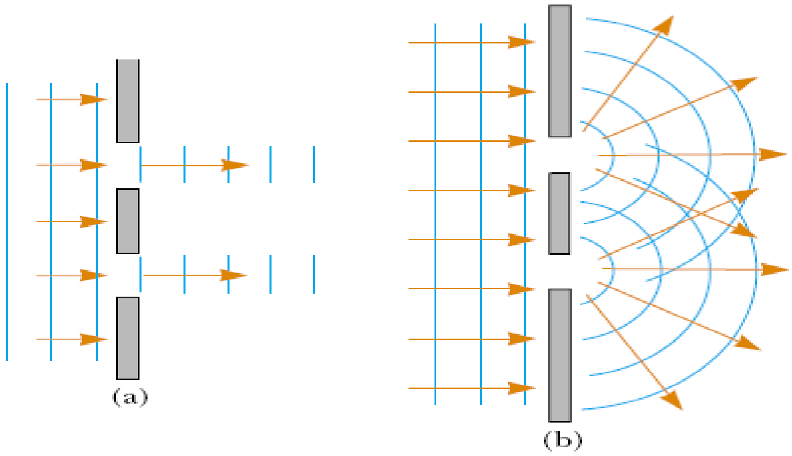


Figure 3 (a) If light waves did not spread out after passing through the slits, no interference would occur. (b) The light waves from the two slits overlap as they spread out, filling what we expect to be shadowed regions with light and producing interference fringes on a screen placed to the right of the slits.

Interference in light waves from two sources was first demonstrated by Thomas Young in 1801. A schematic diagram of the apparatus that Young used is shown in Figure 4a. Plane light waves arrive at a barrier that contains two parallel slits S_1 and S_2. These two slits serve as a pair of coherent light sources because waves emerging from them originate from the same wave front and therefore maintain a constant phase relationship. The light from S_1 and S_2 produces on a viewing screen a visible pattern of bright and dark parallel bands called fringes (Figure 4b). When the light from S_1 and that from S_2 both arrive at a point on the screen such that constructive interference occurs at that location, a bright fringe appears. When the light from the two slits combines destructively at any location on the screen, a dark fringe results.

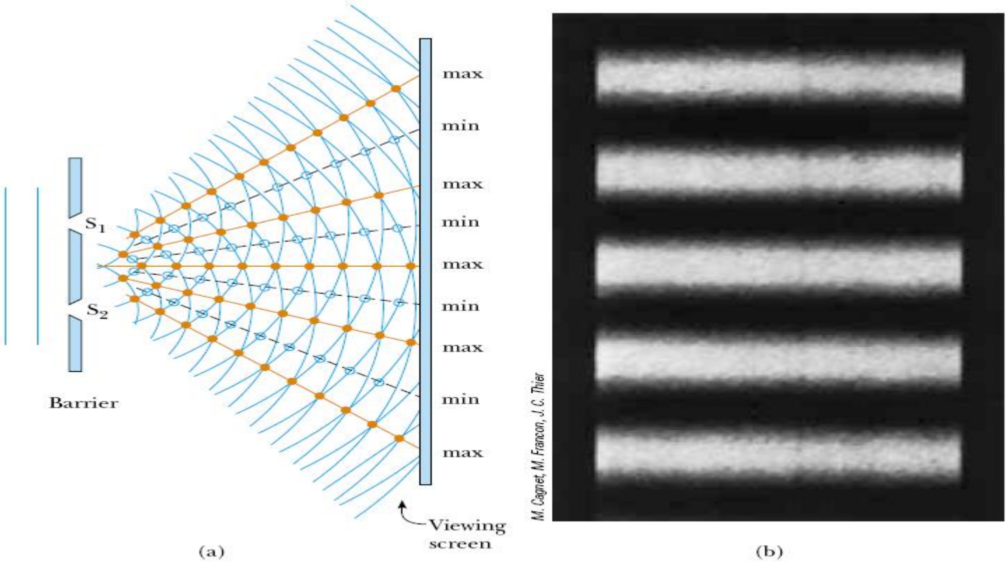


Figure 4 (a) Schematic diagram of Young's double-slit experiment. Slits S1 and S2 behave as coherent sources of light waves that produce an interference pattern on the viewing screen (drawing not to scale). (b) An enlargement of the center of a fringe pattern formed on the viewing screen.

$\Delta = r_2 - r_1 = d \sin\theta$ (path difference)

$d \sin\theta_{bright} = m\lambda$ $m=0, 1, 2, \ldots$ .... (2.9)

$d \sin\theta_{dark} = (m+1/2)\lambda$ $m= 0, 1, 2, \ldots$ .... (2.10)

To obtain expressions for the positions of the bright and dark fringes measured vertically from O to P. In addition to our assumption that L >> d, we assume that d >>λ. These can be valid assumptions because, in practice, L is often on the order of 1 m, d is a fraction of a millimeter and λ is a fraction of a micrometer for visible light. Under these conditions θ is small, so we can use the approximation sinθ = tanθ. Then, from triangle OPQ in figure (5), we see that:

$Y = L \tan \theta \approx \sin\theta$ ……….. (2.11)

Solving equations (2.9, 2. 10) for sin θ and substituting the result into equation (2.11), we find that the position of the bright and dark fringes, measured from O, are:

$Y_{bright} = \frac{\lambda L}{d} m$ m=0, 1, 2,…. ……. (2.12)

$Y_{dark} = \frac{\lambda L}{D} (m + \frac{1}{2})$ m=0, 1, 2,… ……... (2.13)

2.2 Diffraction:

When waves encounter obstacles (or openings), they bend round the edges of the obstacles, if the dimensions of the obstacles are comparable to the wavelength of the waves. The bending of waves around the edges of an obstacle is called diffraction.

Fig. 6 illustrates the passage of waves through an opening. When the opening is large compared to the wavelength, the waves do not bend round the edges. When the opening is small, the bending round the edges is noticeable. When the opening is very small, the waves spread over the entire surface behind the opening. The opening acts an independent source of waves, which propagate in all directions. The diffraction effect is observable quite close to the opening when the size of the opening is very small. When the opening is large, diffraction effect is observed at greater distances from the opening. In general diffraction of waves becomes noticeable only when the size of the obstacle is comparable to a wavelength.

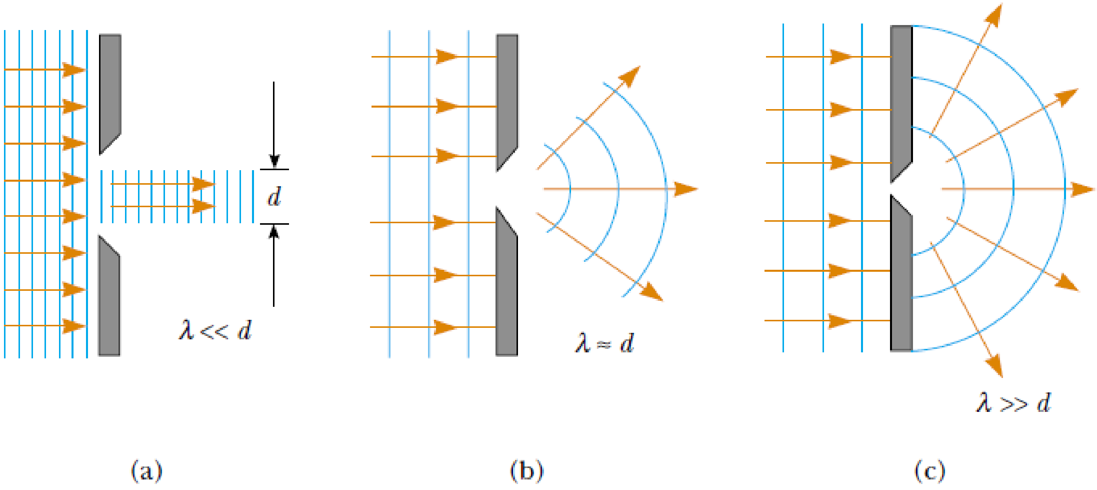


Figure 6 A plane wave of wavelength λ is incident on a barrier in which there is an opening of diameter *d*. (a) When $\lambda << d$, the rays continue in a straight-line path and the ray approximation remain valid. (b) When $\lambda \approx d$, the rays spread out after passing through the opening. (c) When $\lambda >> d$, the opening behaves as a point source emitting spherical waves.

However, diffraction phenomenon is not readily apparent in case of light waves. It becomes significant when the aperture size is of the order of one wavelength wide. Diffraction and interference are basically equivalent.

2.2.1 Distinction between Interference and Diffraction

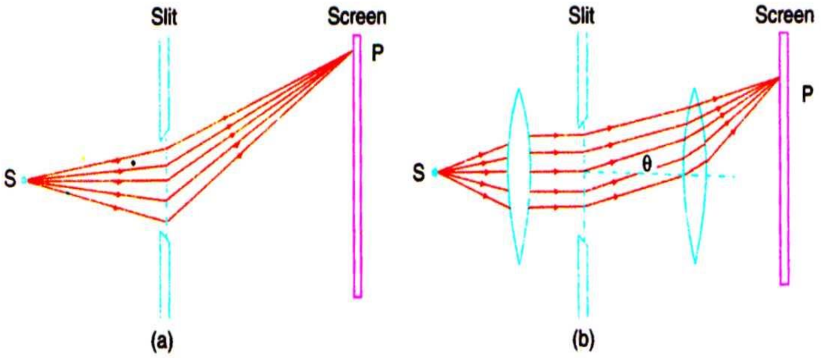
The main differences between interference and diffraction are as follows:

INTERFERENCE	DIFFRACTION
1. Interference is the result of interaction of light coming from different wave fronts originating from the source.	1. Diffraction is the result of interaction of light coming from different parts of the same wave front.
2. Interference fringes may or may not be of the same width.	**2.** Diffraction fringes are not of the same width.
3. Regions of minimum intensity are perfectly dark.	3. Regions of minimum intensity are not perfectly dark.
4. All bright bands are of same intensity.	4. The different maxima are of varying intensities with maximum intensity for central maximum.

2.2.2 Fresnel and Fraunhoflfer types of Diffraction:

The diffraction phenomena are broadly classified into two types: Fresnel diffraction and Fraunhoffer diffraction.

1. Fresnel diffraction: In this type of diffraction, the source of light and the screen are effectively at finite distances from the obstacle (Figure 7a). Observation of Fresnel diffraction phenomenon does not require any lenses. The incident wave front is not planar. As a result, the phase of secondary wavelets is not the same at all points in the plane of the obstacle. The resultant amplitude at any point of the screen is obtained by the mutual interference of secondary wavelets from different elements of unblocked portions of wave front. It is experimentally simple but the analysis proves to be very complex.



Conditions for Fresnel diffraction and Fraunhoffer diffraction.

Fig.(7)

2. Fraunhoffer diffraction: In this type of diffraction, the source of light and the screen are effectively at infinite distances from the obstacle. Fraunhoffer diffraction pattern can be easily observed in practice. The conditions required for Fraunhoffer diffraction are achieved using two convex lenses, one to make the light from the source parallel and the other to focus the light after diffraction on to the screen (Figure 7b). The diffraction is thus produced by the interference between parallel rays. The incident wave front as such is plane and the secondary wavelets, which originate from the unblocked portions of the wave front, are in the same phase at every point in the plane of the obstacle. This problem is simple to handle mathematically because the rays are parallel. The incoming light is rendered parallel with a lens and diffracted beam is focused on the screen with another lens.

2.3 Polarization of Light Waves

We described the transverse nature of electromagnetic waves. Figure (8) shows that the electric and magnetic field vectors associated with an electromagnetic wave are at right angles to each other and also to the direction of wave propagation. The phenomenon of polarization, described in this section, is firm evidence of the transverse nature of electromagnetic waves.

2.3.1 Types of Polarized Light

We can now sum up the various types of polarized light as follows:

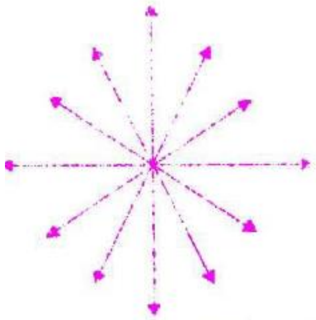
i) unpolarized light, which consists of sequence of wave trains, all oriented at random. It is considered as the resultant of two optical vector components, which are incoherent.

ii) Linearly polarized light, which can be regarded as a resultant of two coherent linearly polarized waves.

iii) Partially polarized light, which is a mixture of linearly polarized light and unpolarized light. Partially polarized light is represented as shown in Figure (9)

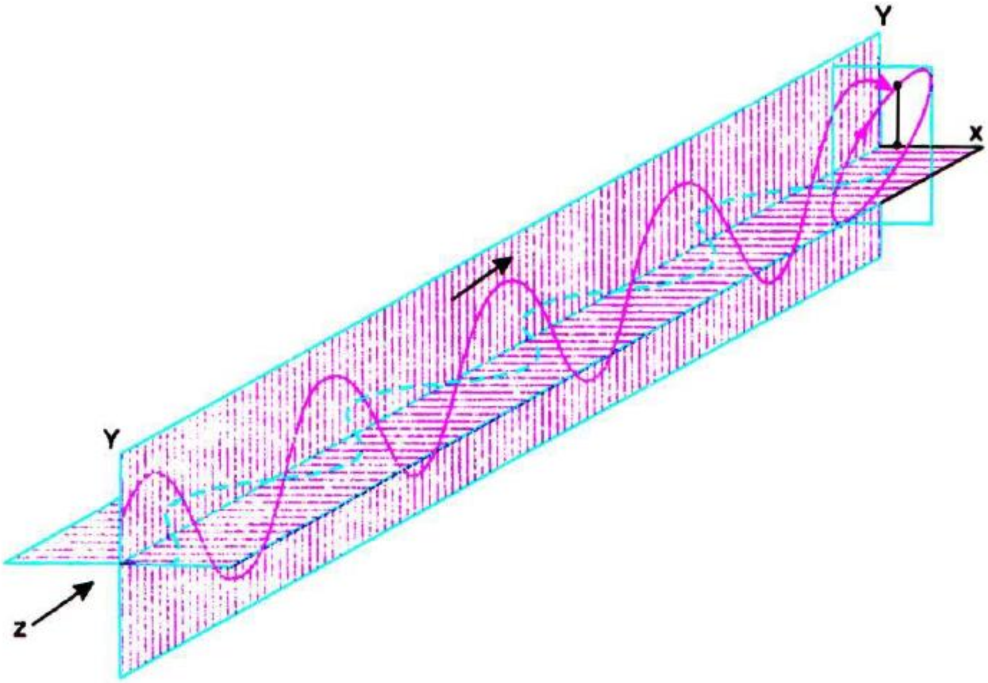
iv) Elliptically polarized light, which is the resultant of two coherent waves having different amplitudes and a constant phase difference of 90° (see Fig. 10). In elliptically polarized light, the magnitude of electric vector E changes with time and the vector E rotates about the direction of propagation.

v) Circularly polarised light, which is the resultant of two coherent waves having same amplitudes and a constant phase difference of 90°. A light wave is said to be circularly polarized, if the magnitude of the electric vector E stays constant but the vector rotates about the direction of propagation such that it goes on sweeping a circular helix in space.



Schematic representation of partially polarized light.

Figure (9)



Elliptically polarised light is produced when two orthogonal coherent waves having different amplitudes and a phase difference of 90°, superpose on each other.

Figure (10)