

Nature of Light

9.1 DUAL NATURE OF LIGHT

The properties and the nature of light was studied by many scientists until about the middle of the seventeenth century. It was generally believed that light consists of a stream of tiny particles or corpuscles. The theory seemed to fit the facts of reflection, transmission and absorption of light. Newton in particular, supported the corpuscular theory of light. The theory suggests that light beam was attracted by the molecules of a denser medium which increased their velocity i.e. higher velocity in denser medium than the velocity in rarer medium.

In 1676, Christien Huygen (1629-1695), showed that a wave theory of light could explain the laws of reflection, refraction and the phenomena of double refraction. Two considerations discouraged Newton and others from accepting Huygen's wave theory. Firstly sound and water waves could bend round obstacles whereas light appeared not to do so, since it produced sharp shadows. Secondly, sound and water waves require a medium for their propagation. How, therefore, could a wave travel through vacuum as light must do to come from the sun and stars? The idea of a wave propagation without medium was unacceptable. One important difference between the theories was that the corpuscular theory of light predicated that light would travel faster in a material medium than air. Whereas the wave theory predicts a slower velocity in a material medium. The velocity of light could not at that time be measured in material, and the decision between the two theories was made on different evidence.

The first clear demonstration that light is a wave phenomena was made by the English physicist, Thomas Young (1773-1829), early in the 19th century. He demonstrated that under certain appropriate conditions, light exhibits an interference behaviour.

Had Newton been alive at the time, he would have appreciated the significance of Young's experiment. Unfortunately, Newton's name had become associated with the corpuscular theory, and admirers of Newton blindly supported the corpuscular theory and ignored the newly proposed theory of light. The wave theory became widely accepted in 1880. The first measurements of the velocity of light in the medium confirmed that the velocity of light is less than in a material medium than in air. Additional developments, such as interference and diffraction of light led to the general acceptance of the wave nature of light.

In secondary classes, the electrostatic field of a distribution of charges at rest and the magnetic field of a steady current in conductor have been studied. These fields may vary from point to point in space, but do not change with time at any individual point. For this situation these fields are regarded independent.

In case, the electric field and the magnetic field do vary with time, then it is not possible to treat the fields independently. According to Faraday's law changing magnetic field with respect to time acts as a source of electric field, similarly a changing electric field with respect to time acts as a source of magnetic field. Therefore, when magnetic field is changing with time, an oscillating electric field is induced in adjacent region of space and when an electric field is changing with time, an oscillating magnetic field is induced.

Consequently, an electromagnetic disturbance consisting of a time varying magnetic field and electric field can be conceived as electromagnetic waves which can propagate through space from one point to another. These paired fields are called collectively the electromagnetic field.

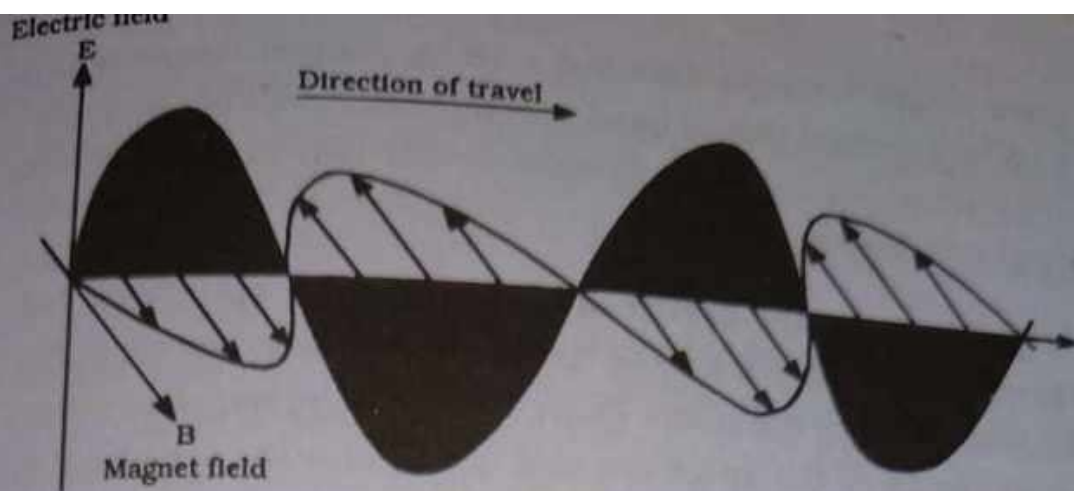


Fig. 9.1 At a large distance from the antenna (located in the negative x direction), the variation of E and B with distance at a given instant is, sinusoidal. Furthermore, the electromagnetic wave is a plane wave and has $E \perp B$ at every point and for all value of the time.

In 1873, James Clark Maxwell showed that these electromagnetic waves can propagate through vacuum. He obtained a theoretical expression for the propagation speed of the electromagnetic waves. The theoretical value of the speed of electromagnetic waves was found to be equal to the speed of light measured experimentally ($c = 2.998 \times 10^8 \text{ ms}^{-1}$).

Thus Maxwell concluded that light waves are electromagnetic waves. (This can also be expressed by stating that light propagates as an electromagnetic wave). These light waves consist of an oscillating electric field E and an oscillating magnetic field B . Both fields are perpendicular to each other. The mutually perpendicular magnetic and electric fields in the light wave oscillate in unison that is, same frequency and identical phase. Both E and B are perpendicular to the direction of propagation of the light waves which is along the x -axis as shown in Fig 9.1. The strength of the electric field at the same location and time is equal to the strength of magnetic field, multiplied by the speed of the light.

Finally, visible light is defined as radiation which can affect the human eye. For the particularly important case of visible light,

the wave length λ ranges from $7.6 \times 10^{-7} \text{ m}$ (longest visible red) to $4.0 \times 10^{-7} \text{ m}$ (shortest visible blue) and the corresponding frequency ν ranges from $3.9 \times 10^{14} \text{ Hz}$ (longest visible red) to $7.5 \times 10^{14} \text{ Hz}$ (shortest visible blue)

Fig 9.2 shows the sketch of electromagnetic spectrum. The electromagnetic spectrum has no definite upper or lower limit. The Fig 9.2 also displays the name given to the electromagnetic waves in various region of the spectrum and it indicates the wavelengths

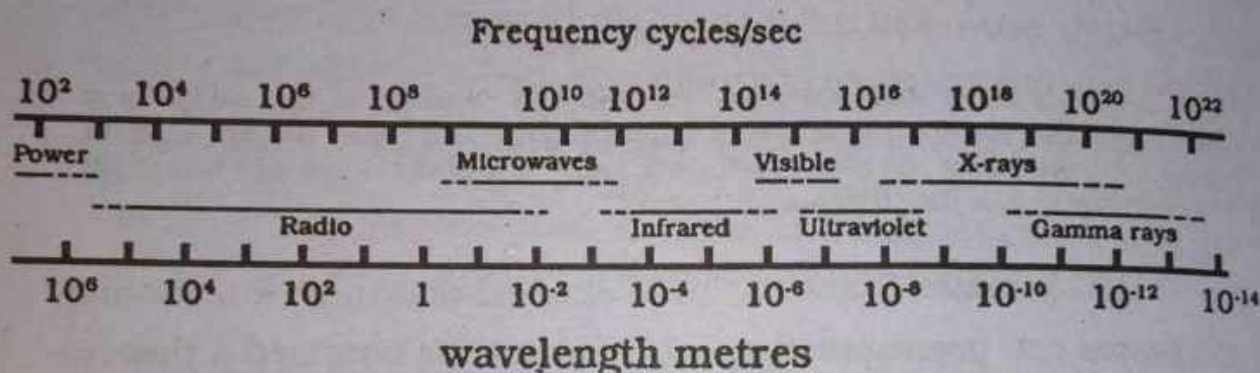


Fig. 9.2 The electromagnetic spectrum. Note that the wavelength and frequency scales are logarithmic.

and frequencies characterizing each. Taken together they constitute electromagnetic radiation.

The wave Theory of light, however, failed to explain the major features of photoelectric effect in which the ejection of electrons from a metal surface takes place when its surface is exposed to light. The experiment showed that.

(i) the Kinetic energy of the ejected photo electrons is independent of the light intensity while the wave theory suggests that Kinetic energy of the photo electrons depends upon the intensity of the light beam.

(ii) For each surface, there exists a cut off frequency. For frequencies less than the cut off frequency, there is no photoelectric effect, whereas according to the wave theory of light, the photoelectric effect should occur for any frequency of the light provided that light intensity is enough.

(iii) No detectable time lag has ever been observed between the impinging of the light on the surface and ejection of the photo electrons, whereas according to wave theory of light there should be a measurable time lag.

In 1905, Albert Einstein successfully explained the photo electric effect by making a remarkable assumption. His theory meets the three objections raised against the interpretation of the photo electric effect based on the wave theory of light. Using Planck's hypotheses of quantized energy exchanged. He proposed that all electromagnetic radiation was in the form of discrete bundles of electromagnetic energy, called photons. Each photon has total energy.

$$E = h\nu$$

Where h is Planck's constant ($h = 6.626 \times 10^{-34}$ J-s) and ν is frequency of the electromagnetic radiation. He further proposed that when a photon interacts with matter, it behaves as a particle and delivers its entire energy to the individual electron in the absorbing surface. In 1921, he received the Nobel Prize in physics for his theory of photoelectric effect.

In 1921, photon nature of light was confirmed by A.H. Compton, which is called Compton effect. He was successful in evaluating the motion of a single electron and a x-ray photon before and after collision between them and concluded that they behaved like material bodies and possess momentum and kinetic energy.

Millikan who experimentally verified the Einstein theory of photoelectric effect was also awarded the Nobel prize in 1923. These are several experiments which demonstrate without any ambiguity that light is composed of photons. The most straightforward photon correlation experiment was reported by Clauser in 1974.

Thus the photoelectric effect and Compton effect supported the corpuscular theory of the light.

To summarize the discussion on the nature of light, we have seen that some phenomena such as interference, diffraction and polarization can be explained on the basis of wave theory of light. Whereas the photo electric effect and compton effect supported the corpuscular theory of the light. Consequently in the process of emission and absorption (to investigate the composition of radiation) it is observed that light radiation have particle- like properties. On the other hand in the phenomena of light propagation (to investigate where the radiation is) it is observed that radiation have wave-like properties. Thus discussion about the nature of light shows that light possesses dual nature i.e. wave-like and particle-like properties.

9.2 WAVE FRONTS, HUYGEN'S PRINCIPLE

In section 9.1, it has been shown that light waves are electromagnetic waves. These light waves consist of mutually perpendicular oscillating electric and magnetic fields. Both electric and magnetic fields are perpendicular to the direction of propagation, therefore, light waves are transverse waves. Waves can be classified as, one dimensional, two dimensional and three dimensional waves depending upon the number of dimensions in which they propagate energy.

Light waves which emanate radially from a small source are three dimensional. Consider a 'single wave', we can draw a surface through all points undergoing a similar disturbance at a given instant. As time passes, this surface moves along indicating how the wave propagates. For a periodic wave train we draw surfaces, all of whose points are in the same phase of motion. These surfaces are called 'wavefronts'. In homogeneous and isotropic medium, the direction of propagation is always perpendicular to the wavefront. A line normal to the wavefronts, indicating the direction of motion of the waves, is called a ray.

Wavefronts can take different shapes. For example, if the disturbances are propagated in a single direction, the waves are then referred as plane waves. Consider a plane normal to the direction

of propagation, here at a given instant conditions are the same everywhere on it. Such wavefronts are called plane wavefronts and the rays are parallel straight lines as shown in Fig 9.3. (a) If the distur-

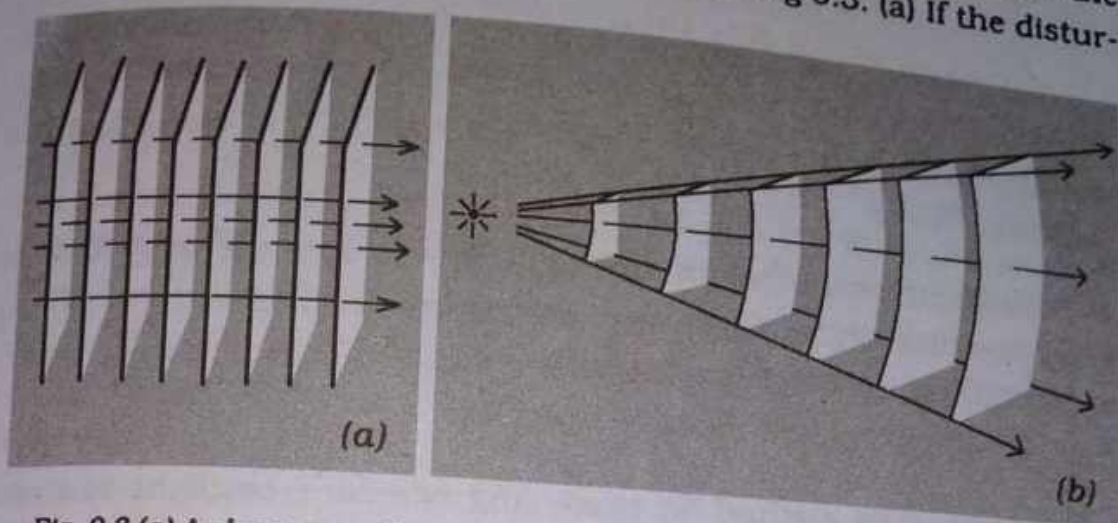


Fig. 9.3 (a) A plane wave. the planes represent wavefronts spaced a wavelength apart, and the represent rays. (b) spherical wave. The rays radial and the wavefronts, spaced a wavelength apart, form spherical shells. Far out from the source, however, small of the wavefronts become nearly plane.

bance is propagated outward in all possible directions from a point source, the resulting wavefronts are spheres and referred as spherical wavefronts while the rays are radial lines leaving the point source in all directions as shown in Fig 9.3(b). At a very large distance from the point source, the spherical wavefronts have very small curvature then a small portion of the spherical wavefront can be treated as plane, i.e. the spherical wavefront reduces to a plane wavefront under certain conditions.

9.3 INTERFERENCE OF LIGHT

In chapter 8, we have studied interference of sound waves which is the result of superposition of two waves. The interference phenomenon of waves, is a general feature of all types of waves such as sound waves, mechanical waves, light waves, etc.

Suppose two waves are allowed to superpose upon each other, if the resultant intensity of the interfering waves is zero or less than the intensity of the individual wave, then this type of interference is called destructive interference. If the resultant intensity of

the interfering waves is greater than the intensity of an individual wave then this type of interference is known as constructive interference.

Light waves also undergo interference. Fundamentally, all interference associated with light waves arises as a result of the combining of the electric and magnetic field vectors that constitute the individual wave.

Interference effect in the light waves are not easy to observe because of the short wavelengths involved (about $4 \times 10^{-7} \text{ m}$ to $7 \times 10^{-7} \text{ m}$). In order to observe stable interference of light wave, the following condition must be obeyed:

A common method for producing two coherent light sources is to use one monochromatic source to illuminate a screen with two small slits as shown in Fig 9.4. The light emerging from both slits is coherent because a single source produces the original light

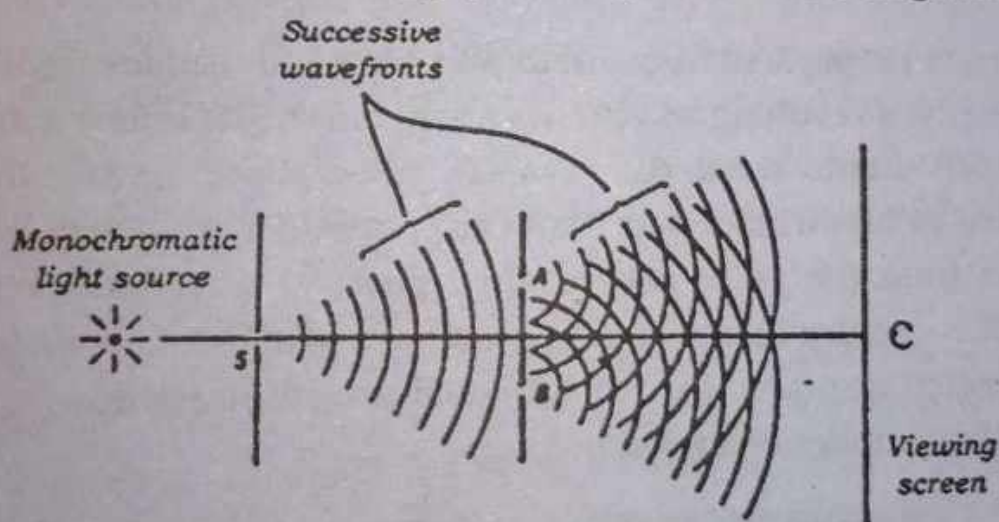


Fig. 9.4 Huygen's Construction of Interference pattern

beam and the two slits serve only to separate the original beam into the parts. Consequently, a random change in the light emitted by the source will occur in the two separate beams at the same time, and interference effects can be observed.

9.4 YOUNG'S DOUBLE-SLIT INTERFERENCE

The phenomena of interference in light waves from two sources was first demonstrated by Thoms Young in 1801. A sche-

matic diagram of the apparatus used by him during demonstration is shown in Fig 9.5(a). To obtain two coherent light sources light is incident on a screen, which has a narrow slit S_0 . The waves emerging from this slit are then allowed to incident on a second screen which has two narrow, parallel slits S_1 and S_2 . These two slits serve as a pair of coherent light sources because waves coming out from these slits originate from the same wavefront and therefore, always in phase. On a screen placed at some distance away, Young found a series of alternately dark and bright parallel bands corresponding to the position of destructive and constructive interference. These alternate dark and bright parallel bands are called fringes. That is, when two light waves add constructively at any location on the screen, a bright fringe is produced and when two light waves add destructively at any location on the screen a dark fringe is produced.

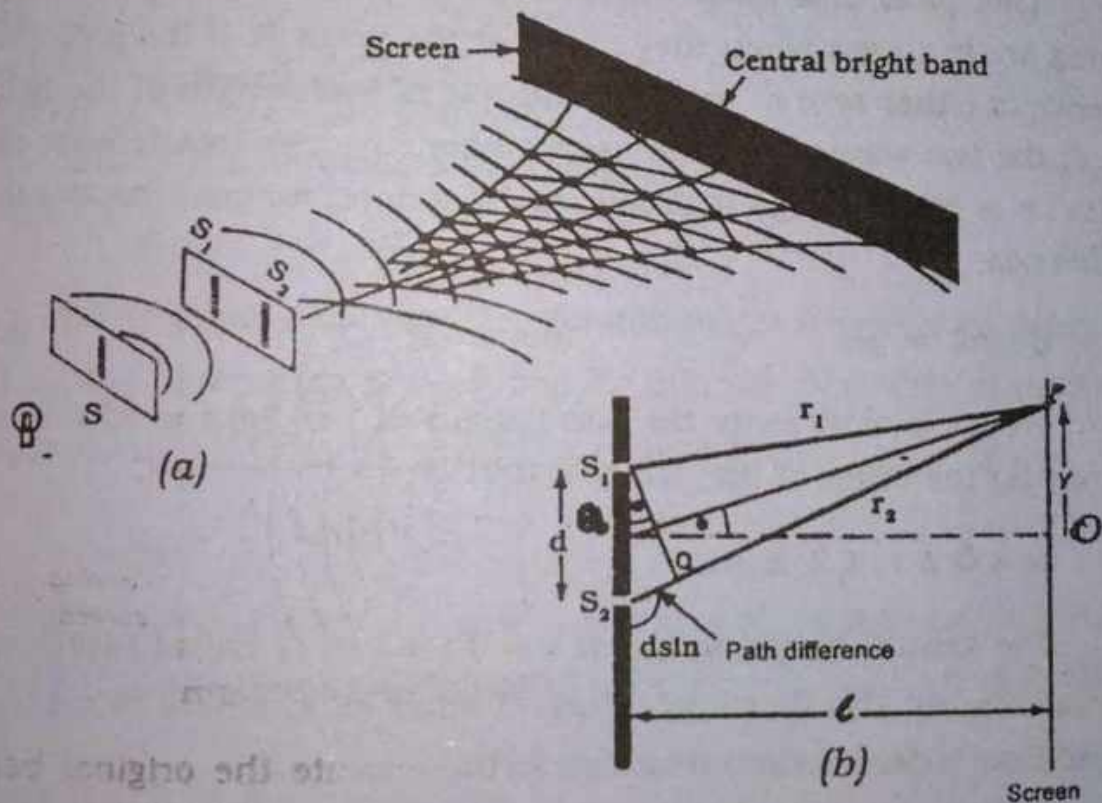


Fig. 9.5 (a) Young's two slit interference pattern. (b) A diagram of the double slit experiment.

The quantitative description of Young's experiment can be obtained with the help of Fig 9.5 (b). Light waves with a definite wave length, λ , are incident on the pair of narrow, slits S_1 and S_2 , which

are separated by a distance d . The interference pattern is observed on a screen which is placed at a perpendicular distance L from the screen containing slits S_1 and S_2 , as shown in Fig 9.5 (b). Consider a point, P , on the viewing screen, suppose.

$$PS_1 = r_1 \text{ and } PS_2 = r_2$$

The light intensity on the screen at the point P is the resultant of the light coming from both slits. Note that a wave coming from the lower slit S_2 travels a greater distance than a wave from the upper slit by an amount equal to the difference between the two paths. the difference between PS_2 and PS_1 is known as path difference. from geometry in Fig. 9.5 (b), we get.

$$PS_2 - PS_1 = (r_2 - r_1) = d \sin \theta \quad 9.1$$

This path difference will determine whether or not the two waves are in phase when they arrive at the point P . If the path difference is either zero or integral multiple of wavelength of the light used, the two waves are in phase and constructive interference results i.e. a bright fringe is produced. Therefore, for constructive interference

$$d \sin \theta = m\lambda \quad (\text{maxima}) \quad 9.2$$

Where λ represents the wavelength of the light used and m stands for the order of the fringes, that is

$$m = 0 \pm 1, \pm 2, \pm 3, \dots$$

The central bright fringe at $\theta = 0$ ($m = 0$) is called zeroth order maximum. The first maximum on other side, where $m = \pm 1$, is called first order maximum and so forth.

Similarly, if the distance $(r_2 - r_1)$ contains an odd number of half wavelength (i.e. an integral number of wavelength plus one-half wavelength), the waves will arrive at the point P with their maxima displaced from one another by half wavelength ($\frac{1}{2}\lambda$). Therefore, at the point P the waves will be out of phase and destructive interference

ence will occur. Thus for destructive interference we have,

$$d \sin \theta = (m + \frac{1}{2}) \lambda \quad (\text{minima}) \quad 9.3$$

Where $m = 0, \pm 1, \pm 2, \pm 3, \dots$

Positions of the bright and dark fringes

It is useful to obtain expressions for the positions of the bright and dark fringes measured vertically from O to P. We shall assume that the distance from the slit to the screen is much larger than the distance between the two slits ($d \ll L$). In practice L is of the order of 1m while d is a fraction of a millimetre under these conditions θ is small, therefore

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

In Fig 9.5(b) consider the triangle OPQ we see

$$\sin \theta = \tan \theta = \frac{Y}{L} \quad 9.4$$

multiplying both sides by d we get

$$d \sin \theta = \frac{Y}{L} d \quad 9.5$$

For computing the position of a m th bright fringe we substitute $y = y_m$ and comparing Eq. 9.5 and Eq. 9.2, the positions of bright fringes measured from the point O are given by

$$y_m \times \frac{d}{L} = m \lambda$$

Where y_m be the distance of the centre of the m th bright band from the centre of the central band at $\theta = 0$

$$y_m = \frac{\lambda L}{d} m \quad 9.6$$

Similarly using Eq. 9.3, and Eq. 9.5, we find that the dark fringes are located at

$$y_d = \frac{\lambda L}{d} (m + \frac{1}{2}) \quad 9.7$$

From Eq. 9.6, we can calculate the distance between two adjacent bright and dark fringes. This distance is known as fringe spacing, Δx . As m increases by unit, we get

$$\text{fringe spacing} = \Delta x = \frac{\lambda L}{d} \quad 9.8$$

As the quantities L and d are measurable, the wavelength of light used can be calculated. In fact Young used this method to obtain the wavelength of light. Additionally, the experiment gave the wave model of light a great deal of credibility.

9.5 INTERFERENCE IN THIN FILMS

Soap bubbles and thin layer of oil floating on water are common examples of thin films. When light is reflected from such a film, we often observe the vivid colours. These visible colour bands are the result of an interference effect. The interference in this case is caused by the interference of light waves reflected from the opposite surfaces of the thin films. We know white light consists of seven colours hence different wavelengths. Therefore the interference may be constructive or destructive depending on the phase relationship of the two interfering beams; hence the appearance of coloured fringes

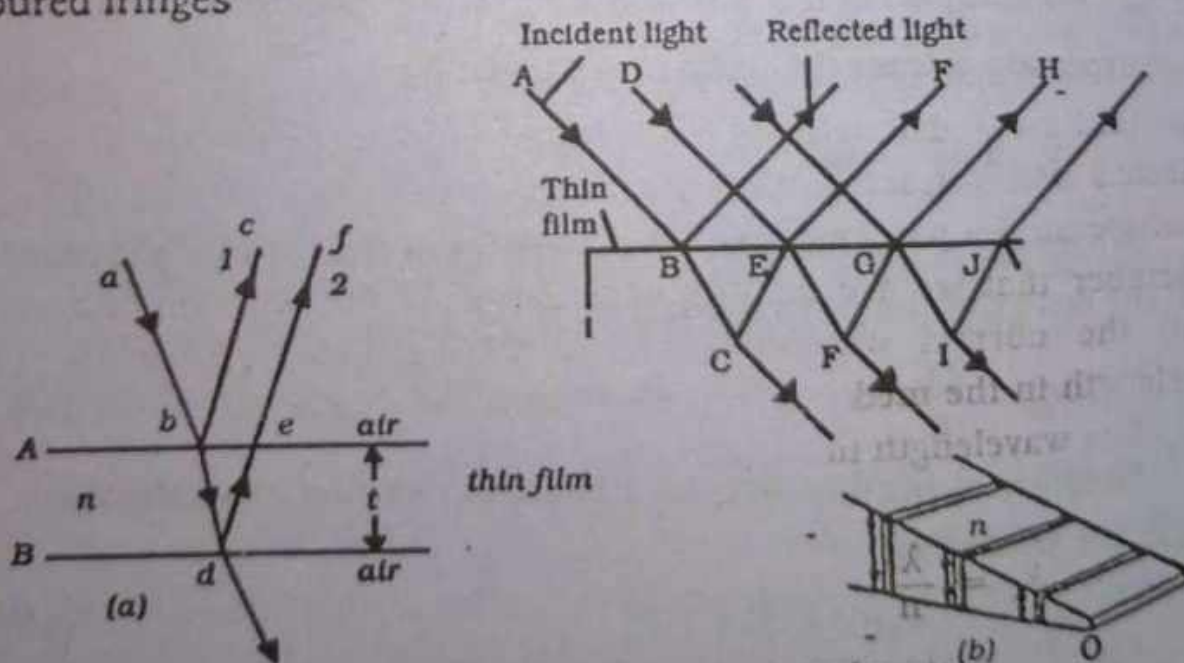


Fig. 9.6 (a) Interference in light reflected from thin film is due to a combination of rays reflected from the upper and lower surfaces
(b) Interference produced by an air wedge.

To investigate the interference effect in thin film, we consider two plates of ultrathin glass plates separated by a thin uniform film of air as shown in fig 9.6(a). The film has a refractive index n and is surrounded by air whose refractive index is 1. We also assume that light waves are coming from a small part of an extended monochromatic source of light (thus relatively coherent) and traveling in air nearly perpendicular to the surface of the film.

In Fig 9.6(a), a line ab represents a ray in a beam of light shining on the upper surface of the film. At the point b on the air-glass interface, the ray ab is partially reflected as a ray be and partially transmitted as a ray bd . On the glass-air interface at the point d , another partial reflection occurs and some of the reflected light emerges as a ray ef . The ray be and ray ef interfere with each other; producing constructive or destructive interference depending on phase relationship. For nearly normal incidence the path difference between the two interfering rays (be and ef) is twice the thickness of the film. Thus path difference $= 2t$.

If this path difference is an integral multiple of wavelength, we expect constructive interference and if the path difference is a half integral number of wavelength destructive interference will occur.

Unfortunately, the situation is not quite simple. First, we must take care what actually happens to the phase of rays that are reflected and refracted, because these two effects have critical influence on the nature of the interference. Furthermore, we must remember that we are dealing with two different wavelengths of light; the normal wavelength λ in air and slightly different wavelength in the medium (of refractive index n) which is labelled as λ_n . The wavelength in medium is then given by



$$\lambda_n = \frac{\lambda}{n}$$

9.9

To investigate what happens to the phase of the rays. When the uniform thickness of the air film is made a thin film of variable thickness (a thin wedge of air), as shown in Fig 9.6(b). Along the

line where the plates are in contacts, there is no path difference and we expect a constructive interference (a bright spot) on the basis of Young's double slit experiment. But in actual experiment this does not happen. What happened? The straight forward conclusion to solve the problem is that one of the two rays has gone under a phase change of 180° during its reflection and therefore, the conditions for the production of constructive and destructive interference on their films are reversed.

In secondary classes you have studied that mechanical waves are reflected whenever they come to a fixed boundary. Observation shows that the reflected pulse is exactly out of phase (180° phase shift) with the original pulse. This phenomenon is as valid in the case of light waves as it is for mechanical waves; therefore the ray bc in Fig. 9.6 (a) which is reflected at the upper surface of the thin film is exactly out of phase (shifted by 180° or half a cycle) with the incoming ray. Refraction has no effect on the phase of the ray and is equivalent to pulse reflecting at the free end- an operation that does not affect the phase of the ray. Thus the ray ef emerges without any change of its phase. It is important to note that a light wave undergoes a phase change of 180° upon reflection from a medium having an index of refraction greater than the index of refraction of the medium in which the wave is travelling.

We conclude that only the ray bc which is reflected from the upper surface of the thin film undergoes phase reversal. The rays bc and ef which are out of phase, interfere with each other. By virtue of the phase shift of 180° (phase reversal) in the ray bc, the condition for the production of constructive and destructive interference are reversed. Because the conditions for the production of constructive and destructive interference in case of Young's double slit experiments are based on the fact that there is no phase reversal in any interfering beam.

In the light of above discussion the condition for constructive interference can be expressed as

$$2t = (m + \frac{1}{2}) \lambda_n; m = 0, 1, 2, 3$$

9.10

substituting, $\lambda_n = \frac{\lambda}{n}$ We get

$$2nt = (m + \frac{1}{2}) \lambda; m = 0, 1, 2, 3, \dots (\text{maxima})$$

9.11

and for destructive interference

$$2nt = m\lambda; m = 0, 1, 2, 3, \dots (\text{minima})$$

9.12

In practice, the interference fringes are not spaced equally in accordance with these equations because these conditions apply strictly only to the light that falls on the thin film at angles about 90° (nearly normal incidence). As remarked earlier the position of fringes depends upon critically on the wavelength of the light used. It is clear that the position for the bright and dark circles will be different for different wavelengths. Hence when white light is reflected and refracted from a thin film produces coloured fringes due to the difference in wavelengths of the colour that is make it up.

9.6 NEWTON'S RINGS

An air wedge may be formed between the curved surface of a plano convex lens and the plane surface of glass shown in Fig. (9.7).

This arrangement produces an interference pattern consisting of a number of rings centered on the point of contact between the lens and the plane surface. These rings are called Newton's rings. The thickness of the air film between the glass surfaces varies from zero at the point of contact to some value 't' at some point E. as shown in fig 9.7.

If the radius of curvature of lens R is very large as compared with the radius r (i.e radius of a ring). The point of contact gives a dark circle due to zero path difference at this point, and 180°

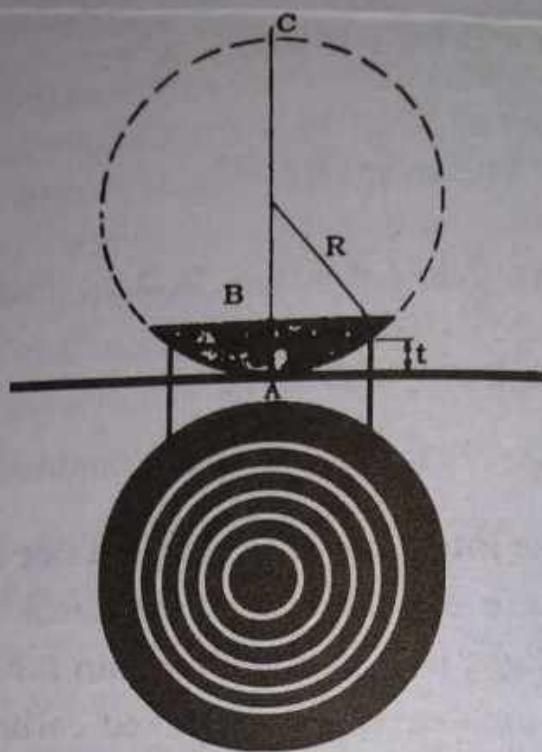


Fig. 9.7 Newton's rings produced by interference at the air wedge formed by the lower surface of the lens and a plane glass surface.

change in phase in the light externally reflected at the lower surface. The photograph of Newton's rings shows a series of dark and bright fringes. These are due to destructive and constructive interference using the geometrical theorem that the product of intercepts of intersecting chords are equal. we have

$$r^2 = (BC) \times (AB)$$

from Fig. 9.7, we write

$$BC = (2R - t), AB = t$$

$$r^2 = (2R - t) \times (t) = 2Rt - t^2$$

t^2 being small is neglected, we get

$$r^2 = 2tR$$

9.13 (a)

$$r = \sqrt{2tR}$$

9.13 (b)

The path difference for constructive interference in this film is given by Eq. 9.11

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

assuming $n = 1$ (for air)

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

for first bright ring ($m = 0$), we write

$$2t_1 = \left(0 + \frac{1}{2}\right) \lambda = \frac{1}{2} \lambda$$

for second bright ring ($m = 1$), we write

$$2t_2 = \left(1 + \frac{1}{2}\right) \lambda = \frac{3}{2} \lambda$$

for third bright ring ($m = 2$)

$$2t_3 = \left(2 + \frac{1}{2}\right) \lambda = \frac{5}{2} \lambda$$

similarly, for N th bright ring. (note that $N = m+1$) we write

$$2t_N = \left((N-1) + \frac{1}{2}\right) \lambda = \left(N - \frac{1}{2}\right) \lambda$$

Substituting $2t_N$ in eq: 9.13 (a) and 9.13 (b), we get

$$r_n^2 = R \left(N - \frac{1}{2}\right) \lambda \quad 9.14 (a)$$

$$r_n = \sqrt{R \left(N - \frac{1}{2}\right) \lambda} \quad 9.14 (b)$$

Example: 9.1

If the radius of the 14th Newton's ring is 1mm, when light of wavelength 5.89×10^{-7} m is used. What is the radius of curvature of the lower surface of the lens used?

Solution

$$r_N^2 = R \left(N - \frac{1}{2}\right) \lambda$$

$$r = 1\text{mm}$$

$$N = 14$$

$$\lambda = 5.89 \times 10^{-4} \text{ mm}$$

Therefore

$$l^2 = R \left(14 - \frac{1}{2} \right) \times 5.89 \times 10^{-4}$$

$$R = 125.7 \text{ mm}$$

9.7 THE MICHELSON INTERFEROMETER

The michelson interferometer was invented by an American physicist A.A. Michelson (1852-1931). The Michelson Interferometer played an interesting role in the history of science during the latter part of the nineteenth century. It has a great scientific importance and had an equally important role in establishing high precision standards of the unit of length. In contrast to the Young's double slit experiment for producing interference fringes which make use of light from two narrow sources, the Michelson Interferometer uses light from a broad, spread source (extended source).

A schematic diagram of the interferometer is shown in Fig 9.8.(a)

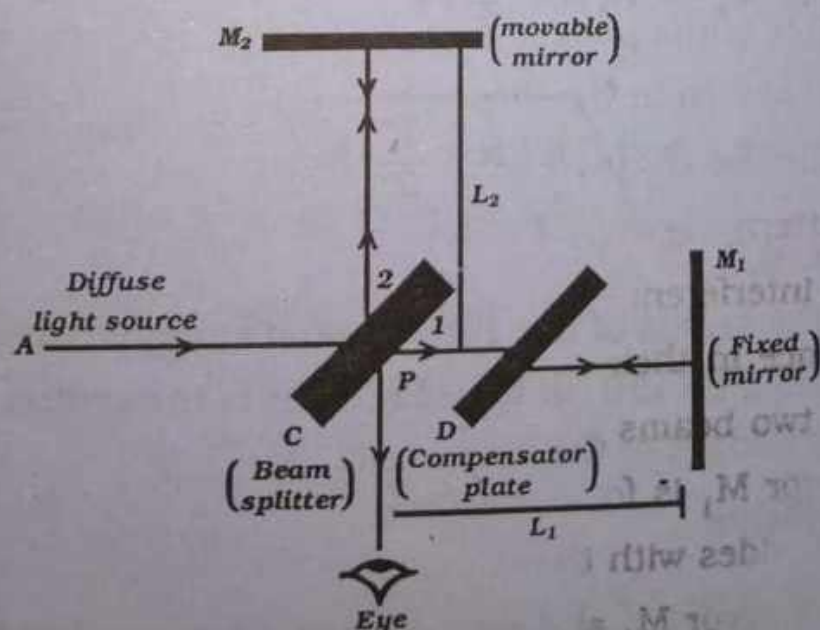


Fig. 9.8 (a) The Michelson interferometer.

It consists of two highly polished plane mirrors M_1 and M_2 . The mirror M_1 is fixed where as the mirror M_2 is movable as shown in the diagram. In addition to this, it has a glass plate C which has a thin coating of silver on its right side. This partially silvered plate is called beam splitter and is inclined at angle of 45° relative to the incident light beam. It has also another plate D which is identical to the plate C except it is not silvered. Its purpose is to ensure that the beam 1 and 2 pass through the same thickness of glass as shown in Fig 9.8.(a) Therefore, it is known as compensating plate. This is particularly important when white light fringes (coloured fringes) are desired. A monochromatic beam of light from an extended source of light A falls on the half silvered plate C. Part of the light is reflected from the silver surface of the beam splitter C (at the point p) to the movable mirror M_2 . After reflection at M_2 it returns to the observer's eye through the plate C. The remaining part of the light passes through silvered surface of the plate C, continues its journey, passes through the compensating plate D and finally falls on the fixed mirror M_1 . The light is reflected back from the fixed mirror M_1 . It passes through the compensating plate D on its return journey and finally it is incident on the silver surface of the plate C from where it is reflected to the observer's eye as shown in the Fig.9.8(a). After reflection from mirror M_1 and M_2 , the two beams eventually recombine to produce an interference pattern which can be viewed.

The interference pattern for the two beams is determined by the difference in their path lengths L_1 and L_2 as shown in figure. When the two beams are viewed as shown, the virtual image (say M_1') of mirror M_1 is formed by reflection at the silvered surface of plate C coincides with the mirror M_2 provided L_1 is exactly equal to L_2 and the mirror M_1 and M_2 are kept exactly at right angles. If L_1 and L_2 are not exactly equal, the image of the mirror M_1 is displaced slightly from M_2 (still parallel to one another); and if the an-

gle between the mirrors is not exactly 90° , the virtual image M_1' of the mirror M_1 makes a slight angle with M_2 . Under this situation, the mirror M_2 and the virtual image M_1' of the mirror M_1 behave in the same manner as the two surfaces of a thin film, and the same sort of interference fringes result from the light reflected from these surfaces. The effective thickness of the air film is varied by moving mirror M_2 parallel to itself. Under these conditions, the interference pattern is a series of bright and dark rings. If the extended source is monochromatic. If a dark ring appears at the centre of the interference pattern, the two beams interfere destructively. If a bright ring appears at the centre of the interference pattern, the two beams interfere constructively.

Suppose the extended source is monochromatic of wavelength λ , and the mirror M_2 is then moved a distance $\lambda/4$, the path difference changes by $\lambda/2$ (twice the separation between M_2 and M_1') a dark ring will appear again at the centre of the interference pattern. Thus, successive dark and bright rings are formed each time M_2 is moved a distance $\lambda/4$. The wavelength of light used is then measured by counting the number of fringes shift for a given displacement of the mirror M_2 . If the displacement is represented by x , then

$$x = m \frac{\lambda}{2} \text{ or } \lambda = \frac{2x}{m}$$

If m is several thousand, the displacement x is large enough so that it can be measured with good precision, and hence a precise value of the wavelength λ can be determined. A common type of Michelson Interferometer used in laboratories is shown in Fig. 9.8 (b).

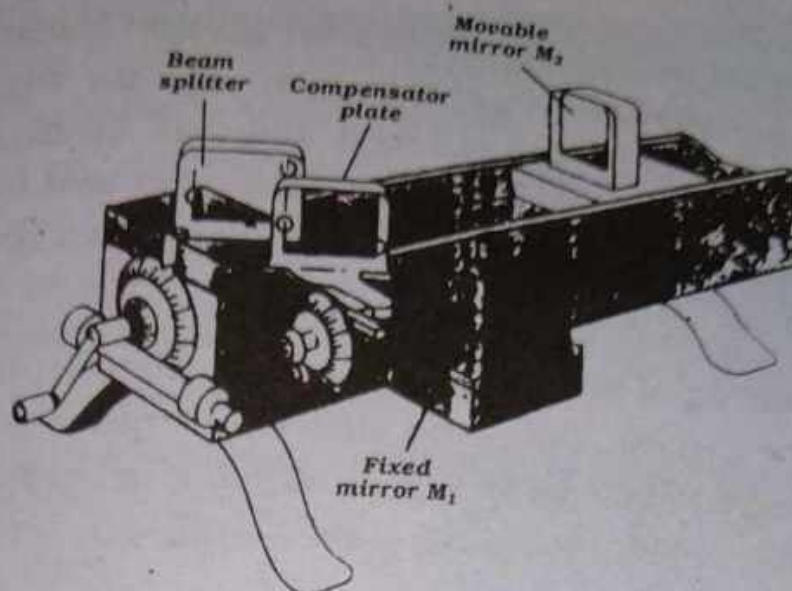


Fig. 9.8 (b) A common type of Michelson interferometer.

9.8 DIFFRACTION

According to the principles of geometrical optics, if we place an opaque object (an object through which light cannot pass) between a point source of light and a screen, a shadow of the obstacle is formed on the screen. In addition, we also observe the following :

- (i) No light reaches within the geometrical shadow of the obstacle at the screen.
- (ii) Outside the geometrical shadow the screen is uniformly illuminated.

Fig. 9.9 shows the shadow of a razor blade placed between a point source of a mono-chromatic light and a photographic plate.

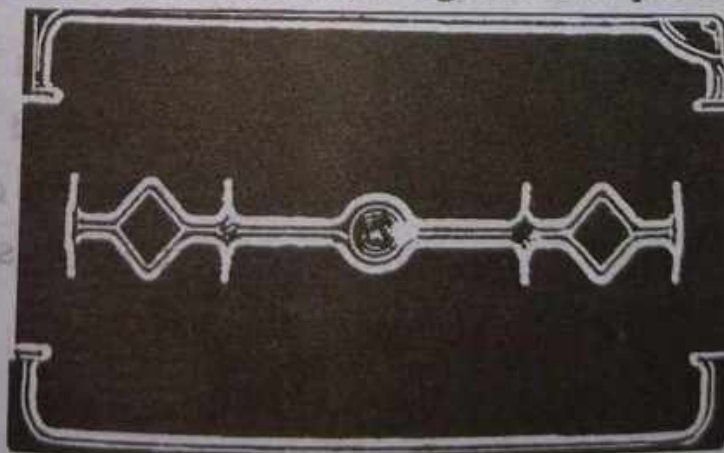


Fig. 9.9 The shadow produced when a razor blade is illuminated by monochromatic point source.

Contrary to what we have observed earlier (no light reaches within the geometrical shadow), we observe that near the edge of the shadow a pattern consisting of bright and dark bands appears. This leads to conclude that some of the light has bent inside the geometrical shadow. "The bending of light around an obstacle is called diffraction."

The bending of light i.e. the diffraction effect depends upon the size of the obstacle. Diffraction effects are larger only when we deal with obstacles or apertures comparable in size to the wavelength. Usually the diffraction effects are small and must be looked carefully.

The phenomenon of diffraction was discovered by Francesco Maria Grimaldi (1618-1663). The diffraction effect was known to Newton (1642-1727), but he did not see in it any justification for a wave theory of light. Huygens although believed in wave theory of light but did not believe in diffraction phenomenon in light. Fresnel (1788-1827) correctly applied Huygen's principle to explain the phenomenon of diffraction which could not be explained on the basis of ray optics.

Diffraction effects are classified in two types.

FRESNEL DIFFRACTION

When both the point source and screen at which the diffraction pattern is formed are kept at finite distance from the diffracting obstacle, the wavefronts falling on the obstacle are not plane; the corresponding rays are not parallel. Similarly the wavefronts leaving the aperture or obstacle to illuminate the screen are not plane as shown in Fig.9.10(a). This situation is described as Fresnel diffraction.

FRAUNHOFER DIFFRACTION

If the source and the screen on which the diffraction pattern is formed are removed at a large distance, so that the correspond-

ing rays are parallel to each other and the wavefronts are plane. This situation is described as Fraunhofer diffraction. This class of diffraction is simpler to treat analytically and can be established in laboratories by using two converging lenses. A lens between distant source of light and obstacle, renders the rays parallel to each other and hence produces plane wavefronts. Whereas second lens collects the parallel set of diffracted rays and focus them at a point on the screen as shown in Fig. 9.10(b and c)

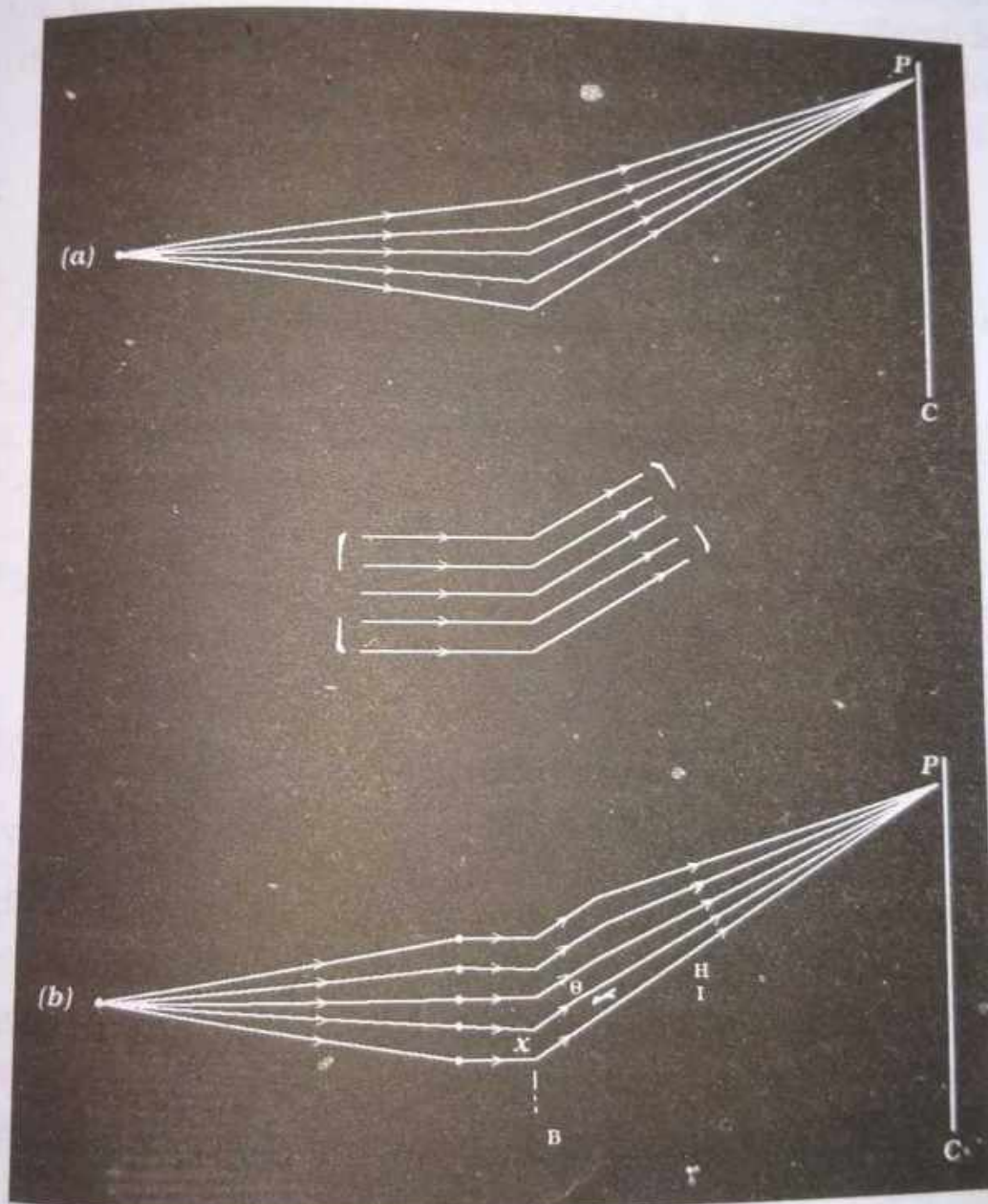


Fig. 9.10 (a) Fresnel diffraction. (b) Source S and screen C are moved to a large distance, resulting in Fraunhofer diffraction. (c) Fraunhofer diffraction conditions produced by lenses, leaving source S and screen C in their original positions.

Single Slit experiment

To understand how dark and bright bands appear in the diffraction pattern inside the geometrical shadow of an obstacle or aperture, we consider a single slit which is gradually narrowed in steps as shown in Fig. 9.11. As the slit gets narrower, the divergence of the diffracted light increases from the slit (i.e. bending around obstacle or aperture increases). In addition, it produces a pattern of light called diffraction pattern as remarked earlier. The centre of the diffraction pattern is bright since the light from all parts of the slit arrives in phase producing maximum intensity due to constructive interference. Single source (i.e. single slit) interference is referred as diffraction and occurs for all kinds of waves

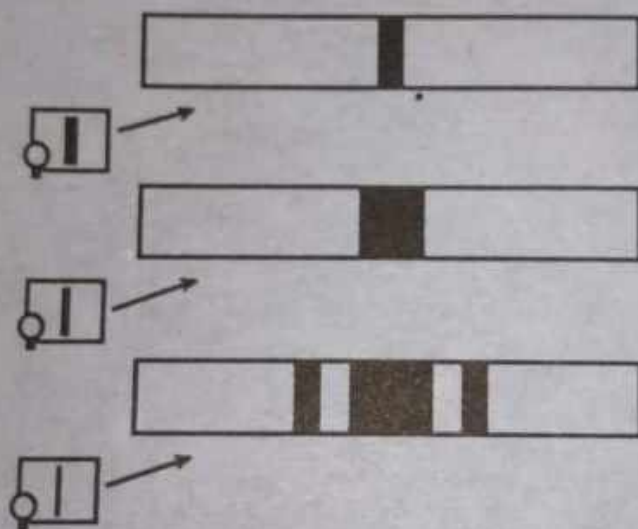


Fig. 9.11 Diffraction pattern of a slit showing the effect of reducing the width of the slit.

Consider a set of parallel rays fall on the slit of width a . The light bends around the edges as shown in Fig. 9.12, we divide the slit into two halves. Mark of equidistant points above and below the centre of the slit such as $c - c'$, $d - d'$, $e - e'$, $f - f'$, ... etc. Suppose the path difference (p.d.) between the rays from the two edges of the slits is one wavelength (1λ) as shown in Fig 9.12. (a)

Obviously the path difference between the rays from the centre point C and C' from the upper edge of the slit is $\lambda/2$ (i.e. 180°). the two rays are out of phase and cancel each other. Similarly the

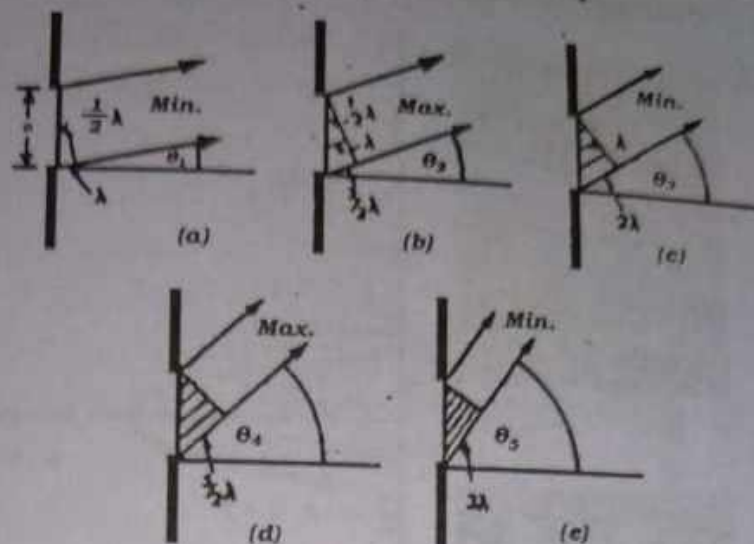


Fig. 9.12 We can obtain the directions of the maxima and minima in a diffraction pattern by dividing up the slit and considering it as a case of interference.

rays from the corresponding pairs of points $d - d'$, $e - e'$, $f - f'$, etc.,... from the lower and upper half of the slit cancel in pairs and produces zero intensity in this particular direction. If the angle increases so that the p.d. between the edges of the slit is $\frac{3}{2} \lambda$, a peak in the intensity occurs.

This is best understood by dividing the slit into three equal parts as shown in Fig: 9.12(b). The light from the upper edge and the central parts interfere destructively, as seen earlier and produces zero intensity. Light from the lowest third part is transmitted uncanceled and results in producing a peak in intensity. Fig. 9.12 (c,d and e) show the path difference is 2λ , $\frac{5\lambda}{2}$, 3λ and the corresponding to each path difference, we get zero intensity, maximum intensity and zero intensity respectively.

Consequently, (using figure) we can write

$$a \sin \theta = 0, \pm \frac{3}{2} \lambda, \pm \frac{5}{2} \lambda, \pm \frac{7}{2} \lambda, \dots \quad (\text{for diffraction maxima}) \quad 9.15$$

$$a \sin \theta = \pm \lambda, \pm 2\lambda, \pm 3\lambda, \pm \lambda, \dots \quad (\text{for diffraction minima}) \quad 9.16 (a)$$

$$\text{or } a \sin \theta = m\lambda; m = \pm 1, \pm 2, \pm 3, \dots \quad 9.16 (b)$$

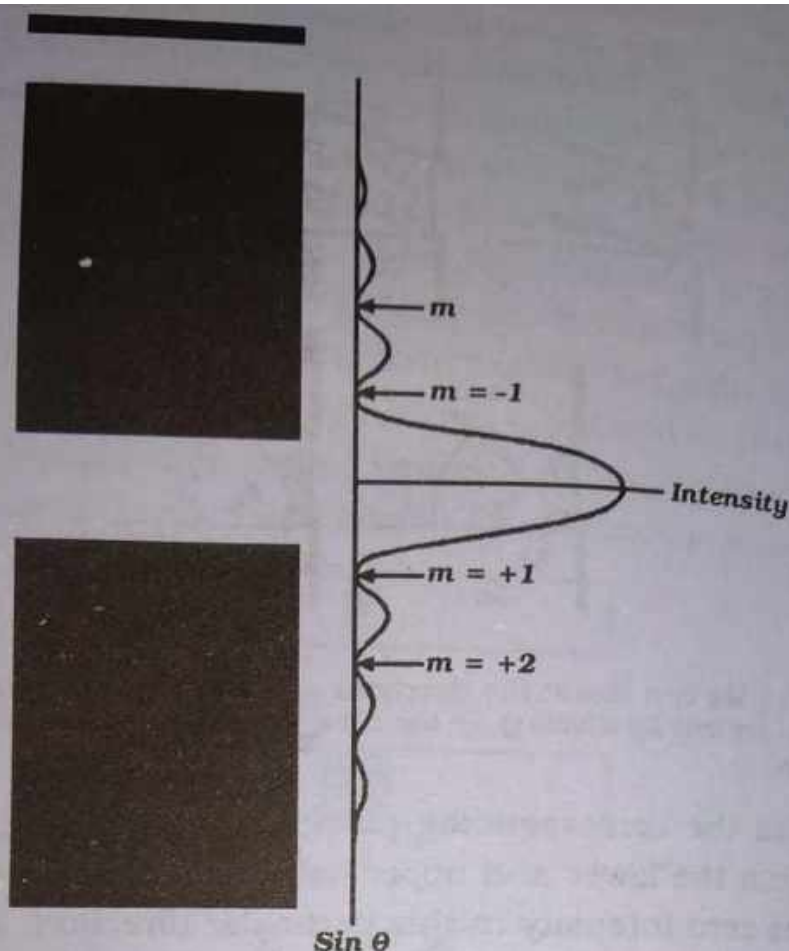


Fig 9.13 (a) Photograph of the diffraction pattern produced by a single slit illuminated by monochromatic light. (b) intensity graph for this diffraction pattern.

The central $m=0$ maximum is very bright since all the wavelets have nearly the same path length and are in phase. The diffraction pattern produced by single slit and the intensity graph for this diffraction pattern when illuminated by a monochromatic light is shown in Fig.9.13.

9.9 DIFFRACTION GRATING

Suppose that instead of a single slit or two slits side by side, we have a very large number of parallel slits, all with the same width and spaced equal distance apart such an arrangement is called a diffraction grating. By using large number of slits, the intensity and the sharpness of lines can be increased, enabling the wave length of the light to be accurately measured.

A diffraction grating is a very useful device for analysing light sources. A diffraction grating consists of a piece of glass with num-

ber of parallel lines marked on it. The thin clear strips between the lines transmit light and act as slits. A fine grating with 6000 lines per cm has a slit spacing d equal to 1.66×10^{-4} cm.

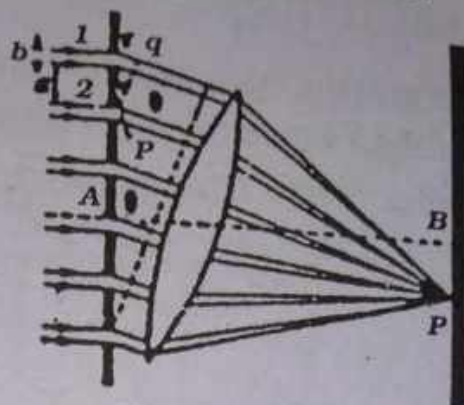


Fig. 9.14 A diffraction grating.

A schematic diagram of plane diffraction grating is shown in Fig: 9.14 where b is the width of slit and a is the separation between two consecutive slits. $(a + b) = d$ is called grating element. A parallel beam of light from the monochromatic source is falling on the grating, which sends out waves from each slit. A convex lens can be used to bring the waves together at a point along certain definite directions, waves of a particular wave length from adjacent slits are in phase and reinforce each other.

The parallel rays of light after diffraction through the grating if differ by one wave length when they arrive at p , they will interfere constructively. The condition for constructive interference is that the path difference between two consecutive waves should be equal to $d \sin \theta$ shown in Flg: (9.14).

For the central maximum there is no path difference, so we call it zero order.

The 1st order maximum occurs when

$$d \sin \theta = \lambda$$

The 2nd order maximum occurs when

$$d \sin \theta = 2\lambda$$

For the m th order maximum

$$d \sin \theta = m\lambda : m = \pm 1, \pm 2, \pm 3$$

Example : 9.2

A diffraction grating with 10000 lines per centimetre is illuminated by yellow light of wavelength 589 nm. At what angles are the 1st and 2nd order bright fringes seen?

Solution

$$d \sin \theta = m\lambda$$

for first order $m = 1$

$$\sin \theta = m\lambda / d = 1 (589 \times 10^{-9}) / (1/10000 \times 1/100) = 0.589$$

$$\sin \theta = 36.1 \text{ degrees}$$

For second order, $m = 2$

$$\sin \theta = m\lambda / d = 2 (589 \times 10^{-9}) / (1/10000 \times 1/100) = 1.178$$

This number is larger than 1 and so $\sin \theta$ does not represent any rational angle.

Hence only the 1st order appears for this wavelength.

9.10 DIFFRACTION OF X-RAYS THROUGH CRYSTALS

X-rays are electromagnetic waves. They have short wave length of the order of 10×10^{-10} m, therefore it is not possible to produce interference fringes of X-rays by Young's double slit method or by thin film method. The reason is that the fringe spacing is given by $\frac{\lambda}{d} \cdot L$ and unless the slits are separated by a distance of the order of 10×10^{-10} m, the fringes obtained will be closed together that they cannot be observed.

However, it is possible to obtain x-rays diffraction by making use of crystals such as rock salt in which the atoms are unifor-

mally spaced in planes and separated by a distance of the order of $2.5\text{\AA}$. Therefore, the diffraction of x-rays takes place when they incident on the crystal as shown in Fig. 9.15.

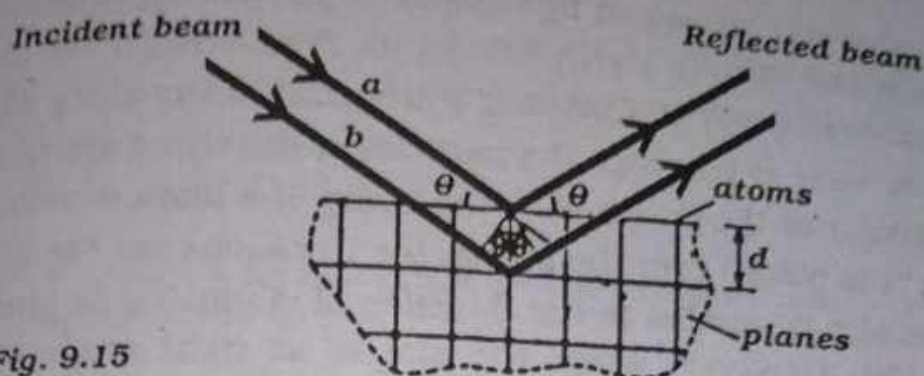


Fig. 9.15

Consider a set of parallel lattice planes having spacing d between each other shown in Fig. 9.15. Consider a and b rays reflected from the two layers separated by a distance d . The path difference between the two reflected rays, is, $LB + BC$ (see Fig 9.15).

It can be proved

$BC = LB = d \sin\theta$, where d is distance between the atomic planes of the crystal. Therefore the path difference $(LB+BC) = 2d \sin\theta$. Now the waves will interfere constructively if the path difference is an integral multiple of the wave length.

$$m\lambda = 2d \sin\theta$$

This relation is called Bragg's Law. The spacing of the atomic layers of crystals can be found from the density and atomic weight. Both m and θ can be measured and hence the wave length of x-rays can be determined from the above equation. Conversely if λ is known, the d may be measured.

9.11 POLARIZATION OF LIGHT WAVES

From the phenomena of interference and diffraction of light it was proved that light has a wave nature. However, this does not tell about the type of waves.

There is a periodic fluctuation in electric and magnetic fields along the propagation of light wave. These fields vary at right angles to the direction of the propagation of the light wave, so light wave is transverse wave.

Transverse nature of light make it possible to produce and detect polarized light. To clarify this let us, first consider the behaviour of transverse waves. Consider a stretched string along which a transverse wave is passing. The particles of the string are vibrating perpendicular to the length of the string. If a block of wood with a slot in it is placed over the string, the vibrations are not affected when the slot is parallel to the direction of vibrations as shown in fig. 9.16 (b). However, when the slot is at right angle to this direction, the vibrations do not pass.

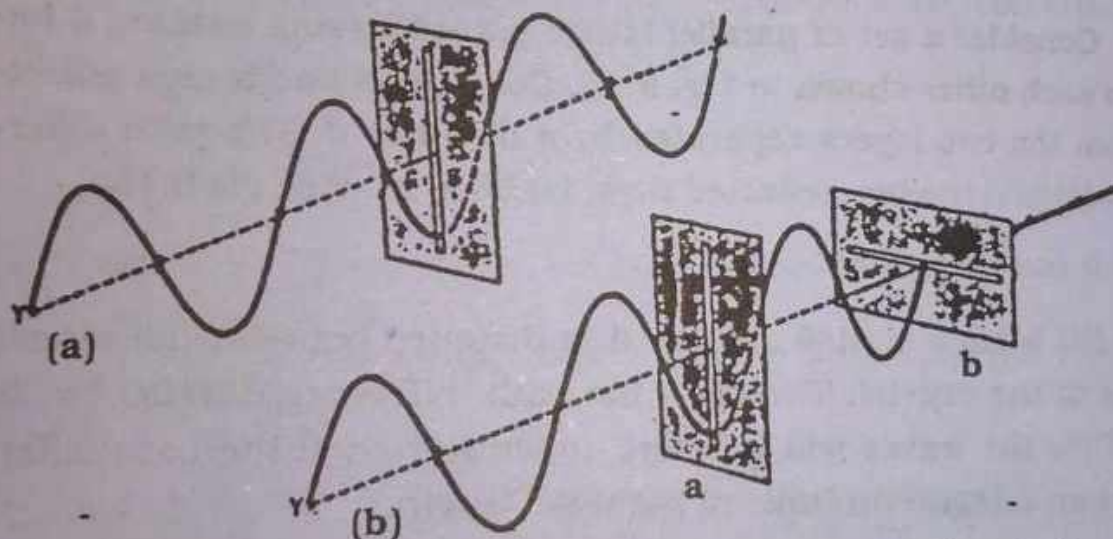


Fig: 9.16 (a) The transverse vibrations on a string are not affected if the slot is (a) parallel to the direction of vibration.

(b) The vibrations do not pass through the slot (b) if it is held perpendicular to the direction of vibration.

A beam of light from the normal source contains large number of waves. The direction of whose vibrations is completely different. This is shown in Fig: 9.17(a). The beam of light is said to be polarized; if an unpolarized beam passes through a polarizing sheet known as polaroid. Unpolarized can be represented as two linearly polarized beams at right angle to each other as shown in Fig: 9.17 (b and c)

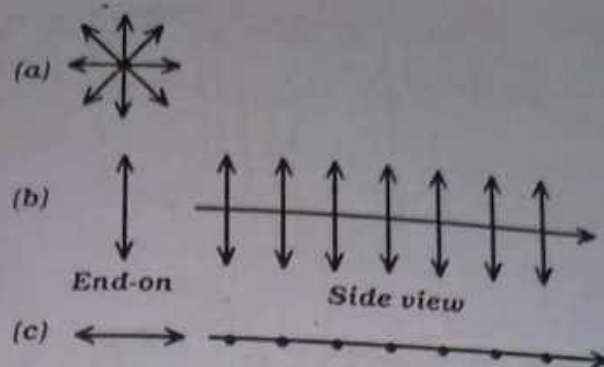


Fig 9.17 (a) unpolarized ordinary light. (b) plane polarized light (c) Polarized perpendicular to paper.

Polarization depends on a parallel arrangement of crystals, which has two effects on the light.

1. It resolves the direction of the vibration of the light wave in to only two directions mutually at right angles.
2. It absorbs one of these components and transmit the other as in Fig: 9.18.

The plane polarized light can be obtained by passing light through a tourmaline crystal. When two tourmaline crystals are placed parallel to each other the light transmitted by the first crystal is also transmitted by the second crystal. When the second crystal is rotated through 90 degrees, no light gets through. The observed effect is due to selective absorption by tourmaline of all light waves vibrating in one particular plane. the second crystal is known as analyser and the first crystal is known as polarizer as shown in Fig: 9.18.

The method of polarizing the light discussed above is called polarization by selective absorption. However, light can be polarized by other methods like reflection, double refraction and scattering of light.

Polarization of light has many technical and scientific applications in daily life. These include :

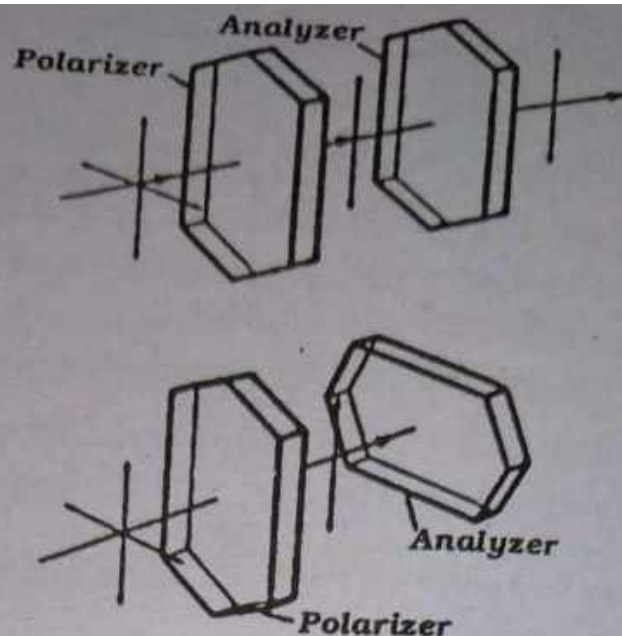


Figure: 9.18

1. The determination of the concentration of optically active substance such as sugar.
2. In photography it is often desirable to enhance the effect of sky and clouds. Since light from the blue sky is partially polarized by scattering a suitable orientated polarizing disc in front of the camera lens will serve as a sky filter.

QUESTIONS

1. Distinguish between diffraction and interference. Can there be diffraction without interference, and interference without diffraction?
2. Describe and explain the interference effect produced by thin films. An observer sees red colour at certain position in an oil film. Would other observers also see the red colour at the same position?
3. Consider YOUNG'S double slit experiment and explain what the following parameters have to do with the light distribution on the screen.
 - (a) Distance between the slits.

- (b) Width of the slits.
- (c) Wavelength of the incident light.
4. Give an experimental arrangement for producing Newton's rings. Why are the fringes circular and why is central spot black? Would the point of central spot appears dark if seen with the help of transmitted light?
 5. Discuss the statement that a diffraction grating could just as will be called an interference grating?
 6. For a given family of planes in a crystal, can the wavelength of incident X-rays be:
 - (a) too large or
 - (b) too small to form a diffracted beam?
 7. What do you mean by plane polarized light? How does the phenomena decide that light waves are transverse?
 8. Why Maxwells discovery that light was an electromagnetic wave is so important?
 9. Which of the following can occur in (a) transverse and (b) longitudinal waves?

Refraction, Dispersion, Interference, Diffraction, and Polarization.

PROBLEMS

1. How many fringes will pass a reference point if the mirror of a Michelson's interferometer is moved by 0.08mm. The wavelength of light used is 5800Å.
(Ans. 275)
2. In a double slit experiment the separation of the slits is 1.9mm and the fringe spacing is 0.31mm at a distance of 1 from the slits. Find the wavelength of light?
(Ans. -0.589×10^{-6} m)
3. Interference fringes were produced by two slits 0.25mm apart on a screen 150mm from the slits. If eight fringes occur

py 2.62mm. What is the wavelength of the light producing the fringes?
(Ans. $5.46 \times 10^{-7} \text{ m}$)

4. Green light of wavelength $5400 \text{ \AA}$ is diffracted by grating having 2000 lines cm.
(a) Compute the angular deviation of the third order image.
(b) Is a 10th order image possible?

Ans. (a) 189° (b) Impossible.

5. Light of a wavelength $6 \times 10^{-7} \text{ m}$ falls normally on a diffraction grating with 400 lines per mm. At what angle to the normal are the 1st, 2nd, and 3rd order spectra produced?

Ans. 13.9° , 28.7° , 46.1°

6. If a diffraction grating produced a 1st order spectrum of light of wavelength $6 \times 10^{-7} \text{ m}$ at an angle of 20° from the normal. What is its spacing and also calculate the number of lines per mm?

(Ans: $1.75 \times 10^{-3} \text{ mm}$, $5.7 \times 10^2 \text{ lines / mm}$)

7. Newton's rings are formed between a lens and a flat glass surface of wavelength $5.88 \times 10^{-7} \text{ m}$. If the light passes through the gap at 30° to the vertical and the fifth dark ring is of diameter 9mm. What is the radius of the curvature of the lens?

(Ans. 23.8m)

8. How far apart are the diffracting planes in a NaCl crystal for which X-rays of wavelength $1.54 \text{ \AA}$ make a glancing angle of $15^\circ - 54'$ in the 1st order?

(Ans. $2.81 \text{ \AA}$)

9. A parallel beam of X-rays is diffracted by rock salt crystal the 1st order maximum being obtained when the glancing angle of incidence is 6 degree and 5 minutes. The distance between the atomic planes of the crystal is $2.81 \times 10^{-10} \text{ m}$. Calculate the wavelength of the radiation.

(Ans. $0.5952 \times 10^{-10} \text{ m}$)