

Unit 9

PHYSICAL OPTICS

Major Concepts

(25 PERIODS)

Conceptual Linkage

This chapter is built on
Properties of Waves Physics
IX

- Nature of light
- Wave front
- Huygen's principle
- Interference
 - Young's double slit experiment
 - Michleson's Interferometer
- Diffraction
- Polarization

Students Learning Outcomes

After studying this unit, the students will be able to:

- Describe light waves as a part of electromagnetic waves spectrum.
- Describe the concept of wave front.
- State Huygen's principle and use it to construct wave front after a time interval.
- State the necessary conditions to observe interference of light.
- Describe Young's double slit experiment and the evidence it provides to support the wave theory of light.
- Explain colour pattern due to interference in thin films.
- Describe the parts and working of Michleson Interferometer and its uses.
- Explain diffraction and identify that interference occurs between waves that have been diffracted.
- Describe that diffraction of light is evidence that light behaves like waves.
- Describe and explain diffraction at a narrow slit.
- Describe the use of a diffraction grating to determine the wavelength of light and carry out calculations using $d \sin \theta = n\lambda$.
- Describe the phenomena of diffraction of X-rays through crystals.
- Explain polarization as a phenomenon associated with transverse waves.
- Identify and express that polarization is produced by a Polaroid.
- Explain the effect of rotation of Polaroid on Polarization.
- Explain how plane polarized light is produced and detected.

INTRODUCTION

The properties and the nature of light was studied by many scientists based on different theories but two of them were commendable, that is Newton's corpuscular theory and Christian Huygen's wave theory. Newton believed that light consists of small particles called corpuscles and he was successful in reflection and refraction phenomena. There are two experiments photoelectric effect and Compton's effect which have been verified the Newton's corpuscular theory and these will be studied in Modern physics in the next class.

In 1676, Huygens explained the light in terms of wave. According to this wave theory, light is travelling in the form of a wave. The wave theory can explain reflection, refraction and the phenomenon of double refraction. The Huygen's wave theory of light was not acceptable by Newton and others. Because the knowledge of waves was confined to mechanical waves only and it requires some medium for its propagation and there was no idea about electromagnetic waves. Therefore, Huygen proposed hypothetical medium Ether. One important difference between the two theories was that the corpuscular theory predicted that light would travel faster in a material medium than air, whereas the wave theory predicted a slower velocity in a dense medium. Later on, it was proved experimentally that the velocity of light is faster in rare medium.

Similarly, James Clark Maxwell presented the idea of electromagnetic waves. Electromagnetic waves can propagate through vacuum. It has same properties as that of the light and the speed of this wave is equal to speed of light i.e. $3 \times 10^8 \text{ m s}^{-1}$. Thus, Maxwell concluded that light waves are electromagnetic waves and require no medium such as ether for their propagation.

In 1801, Young provided an experimental proof of wave theory of light by performing interference of light. Similarly, the result of diffraction is also a strong evidence of the wave theory of light. The polarization phenomenon has confirmed that transverse nature of light wave. The discussion about the nature of light shows that light possess dual nature. Sometimes it behaves like particles but sometimes it behaves like waves. But it may be noted that these both behaviours cannot be considered simultaneously. The particle nature of light will be studied in modern physics meanwhile we will have studied wave nature of light in the present chapter.

POINT TO PONDER

Can you tell whether the unit of intensity of light is based or derived?

9.1 WAVE FRONT

When a stone is dropped into a pond of still water then there is expanding series of circles formed by crests and troughs. Like water waves, concentric circles of light waves can be drawn that propagate from a source of light in all directions

with speed ' c ', as shown in Fig.9.1. The radius of each circle is " ct " and each circle has the same displacement from the centre of source ' S ' moreover, all the particles on each circle have same phase. "The surface on which all the points vibrate in the same phase in a homogenous medium is known as a wave front".

A line perpendicular to the wave fronts indicating the direction of motion of the waves is called a ray.

When there is a point source and medium is homogenous and isotropic then we have spherical wave fronts. In this case, the direction of propagation of the wave is always normal to the wave front.

If the disturbance is propagated in a single direction, the waves are then represented as plane waves and its corresponding wave fronts are called plane wave fronts as shown in Fig.9.2.

9.2 HUYGENS'S PRINCIPLE

Huygens's principle is a geometrical method used to develop a new wave front from the information of shape and position of the primary wave front. According to Huygen wave theory, light travels in the form of waves and all the points of primary wave front behave as secondary sources emitting wavelet in phase with one another which spread out in forward direction with a speed equal to the speed of propagation of the wave.

Let a source S produced a primary wave front AB at instant ' t ' as shown in Fig.9.3. The dots on the primary wave front AB behave as secondary sources which produce hemisphere each of radius ' $c\Delta t$ ', known as wavelets.

The surface which touches all the wavelets from the secondary sources is

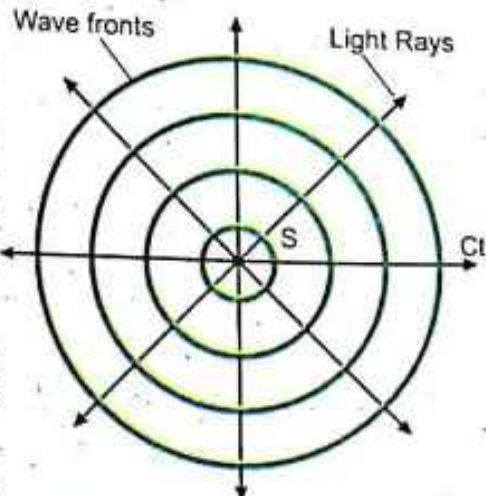


Fig.9.1: Spherical Wave Fronts

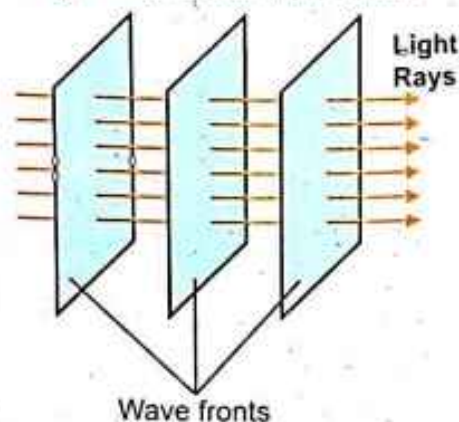


Fig.9.2: Plane wave fronts

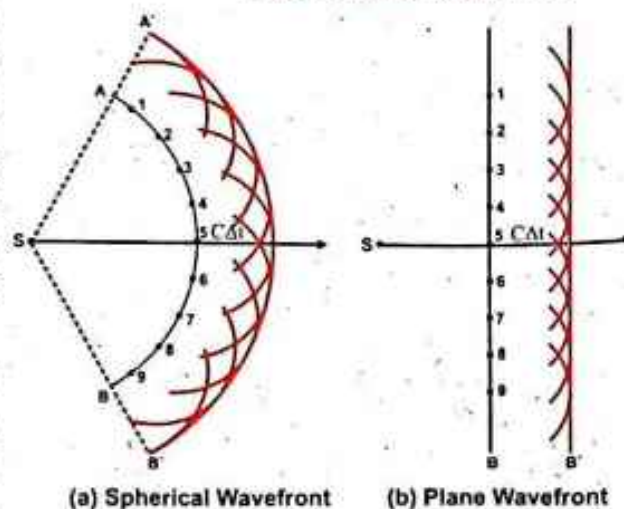


Fig.9.3: The wave fronts which are obtained under the Huygen's principle
(a) Primary spherical wavelets at ' t ' and secondary spherical wavelets at $t + \Delta t$.
(b) Primary plane wavelets at ' t ' and secondary plane wavelets at $t + \Delta t$.

the new wave front A'B' at instant $t + \Delta t$ for next wave front, the same process is repeated.

In this way, an infinite number of spherical wave fronts are formed. If the medium is homogenous then equal amount of energy is transmitted in all direction by these waves. Similarly, if the medium is non-homogenous then we have a plane primary wave front AB and also Huygen's principle can be applied for the secondary wave front A'B' as shown in Fig.9.3.

9.3 INTERFERENCE OF LIGHT WAVES

We have studied interference of sound waves in the previous chapter. Now we discuss the interference of light waves. As interference of light is difficult to observe due to the random emission of light from the source. The following conditions should be fulfilled in order to observe the interference phenomenon of light waves.

1. The sources should be monochromatic i.e. these should emit waves of single wavelength.
2. The sources should be coherent which produce waves of same frequency with zero or constant phase difference.
3. The two sources should be closed to each other.

Consider two coherent waves in the same medium which are superimposed with each other. At some points there is enhancement in amplitude and at other points there is cancellation in amplitude. As a result, we have constructive and destructive interference and therefore bright and dark fringes are obtained on a screen as shown in Fig. 9.4. This phenomenon is known as interference of light waves.

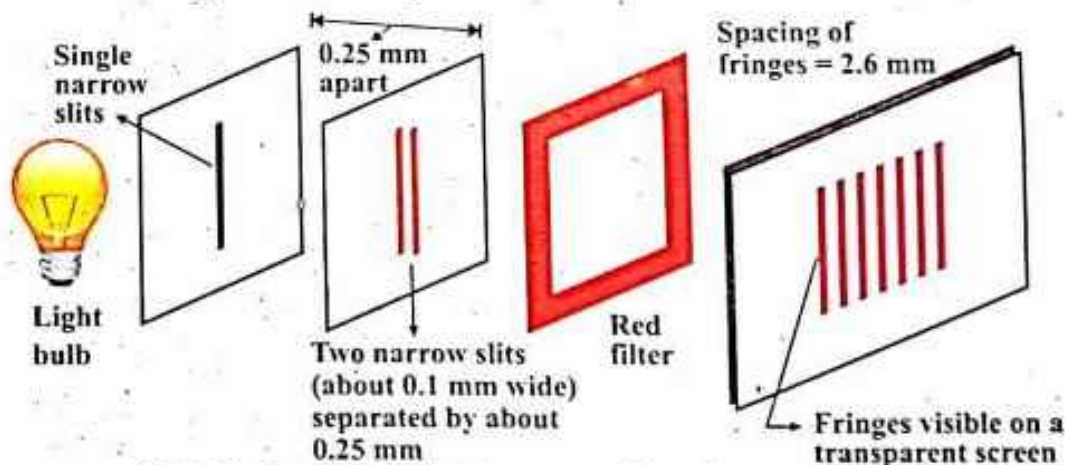


Fig.9.4: Experimental arrangement of interference of light

Constructive Interference

When two coherent waves are superimposed such that the crest of one wave coincide with crest of the other wave and trough with trough then the amplitude of its resultant is greater than that of the amplitude of individual wave as shown in Fig.9.5. This type of interference is called constructive interference.

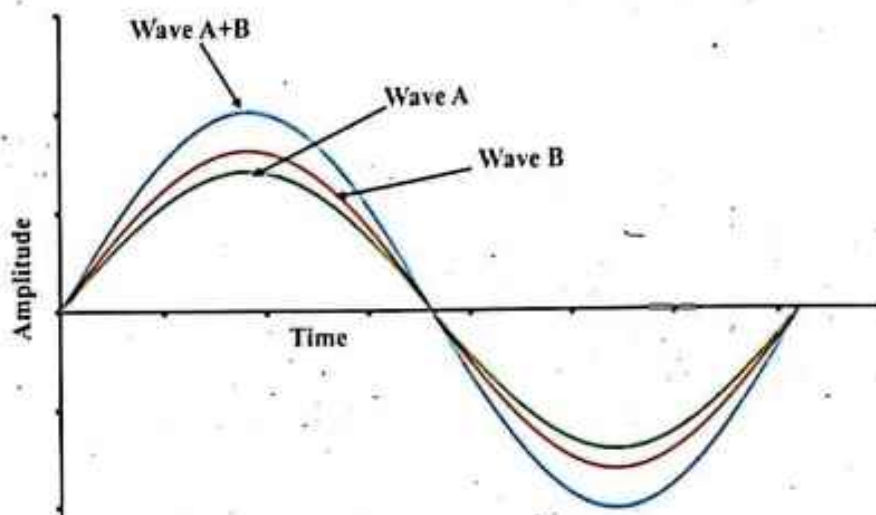


Fig.9.5: Constructive Interference due to the combination of coherent light waves in same phase.

Destructive Interference

In destructive interference, the superposition of two coherent waves, takes place in such a way that the crest coincide with trough and trough with crest and the amplitude of the resultant wave is less than the amplitude of individual wave as shown in Fig. 9.6.

9.4 YOUNG'S DOUBLE SLIT EXPERIMENT

This is the very first experiment on interference of light, which was demonstrated by Young in 1801. The result of this experiment provides a strong evidence for Huygens's wave theory.

The experimental setup consists of a source of monochromatic light which is placed in front of a narrow slit 'S'. Two slits S_1 and S_2 of the same size and separated by small distance are placed in front of narrow slit 'S'. These two slits act as two coherent sources as shown in Fig.9.7. Now the light waves from these two slits are superimposed at different points then interference occurs.

The points where crests fall on crests or troughs fall on troughs produces constructive interference and we have bright fringes.

On the other hand, those points where

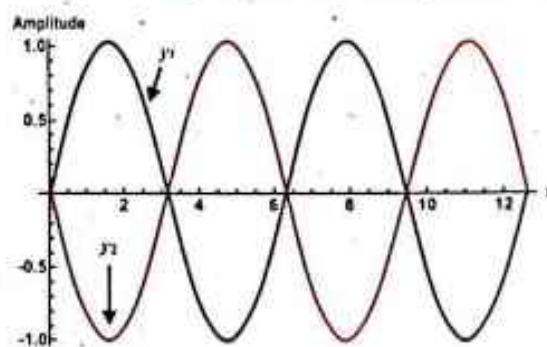


Fig.9.5: Destructive Interference due to the combination of coherent light waves in different phase.

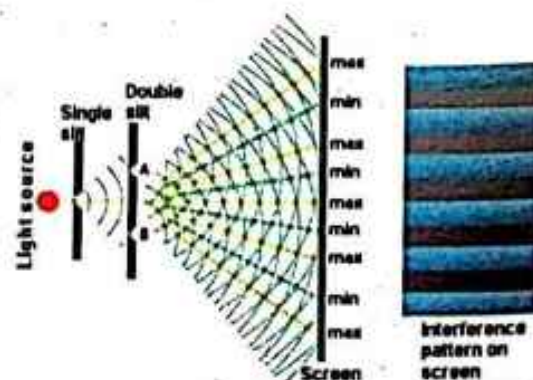


Fig.9.7: Bright and dark fringes that obtained due to the super position of two coherent waves in the Young double slit experimental arrangement.

crests fall on troughs produce destructive interference and we have dark fringes. In this way, a series of bright and dark fringes is obtained on the screen which is placed at some distance from the slits. The result of Young's double slit experiment can also be studied analytically as well.

Let 'd' be the distance between two slits S_1 and S_2 , 'L' be the distance between centre of slits and centre of the screen and 'y' be the distance of any fringe from the centre of the screen.

In order to derive equations for bright and dark fringes, we consider a point 'P' on the screen at distance QP from the centre of screen. S_1P and S_2P are the two rays from S_1 and S_2 respectively reaching at P. The path difference between S_1P and S_2P can be determined by drawing a perpendicular from S_1 on S_2P .

As $S_1P = RP$ as shown in Fig. 9.8, so S_2R is a path difference between the two rays.

In triangle S_1S_2R

$$\frac{S_2R}{S_1S_2} = \sin \theta$$

$$S_2R = S_1S_2 \sin \theta$$

$$[\because S_1S_2 = d]$$

$$S_2R = d \sin \theta$$

$$\text{Path difference } (S_2R) = d \sin \theta \dots\dots(9.1)$$

In interference pattern, bright fringes will be observed on the screen when path difference between two rays is given by

$$\text{Path difference } (S_2R) = m\lambda \dots\dots(9.2)$$

$$\text{where } m = 0, \pm 1, \pm 2, \pm 3, \dots$$

Comparing equations (9.1) and (9.2)

$$d \sin \theta = m\lambda \dots\dots(9.3)$$

Similarly, for destructive interferences (dark fringes)

$$\text{Path difference } (S_2R) = \left(m + \frac{1}{2}\right)\lambda \dots\dots(9.4)$$

Comparing eq. 9.1 and eq. 9.4

$$d \sin \theta = \left(m + \frac{1}{2}\right)\lambda \dots\dots(9.5)$$

where

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

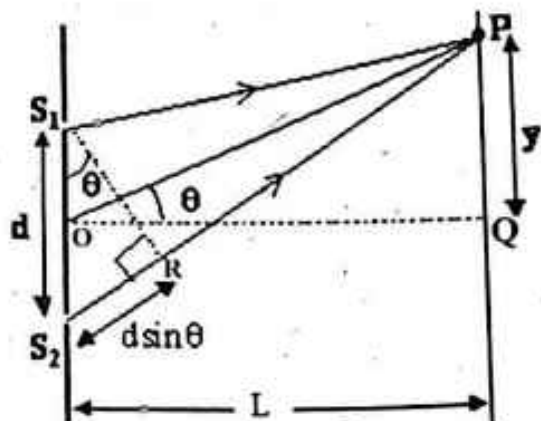


Fig.9.8: Two rays from two slits S_1 and S_2 which are incident on a screen at point P such that S_2R is a path difference between them.

Now if angle ' θ ' is very small then

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

From triangle OPQ

$$\tan \theta = \frac{PQ}{OQ}$$

$$\tan \theta = \frac{y}{L}$$

Equation 9.3 becomes.

$$d \tan \theta = m\lambda$$

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

$$y = \frac{m\lambda L}{d} \quad \text{.....(9.6)}$$

Equation (9.6) gives the position of bright fringe

Similarly,

$$d \tan \theta = \left(m + \frac{1}{2}\right) \lambda$$

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

$$y = \left(m + \frac{1}{2}\right) \frac{\lambda L}{d} \quad \text{.....(9.7)}$$

Equation 9.7 gives the position of dark fringe

Fringe Spacing

Fringe spacing is defined as the distance between two consecutive bright fringes or two dark fringes.

Width of bright fringe $\Delta y = y_{m+1} - y_m$

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

$$\Delta y = \frac{L}{d} m \lambda + \frac{\lambda L}{d} - \frac{L}{d} m \lambda$$

$$\Delta y = \frac{\lambda L}{d} \quad \text{.....(9.8)}$$

Width of dark fringes $\Delta y = y_{m+1} - y_m$

FOR YOUR INFORMATION

θ°	$\sin \theta$	$\tan \theta$
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

POINT TO PONDER

Can you perform the interference phenomenon by using the sun light?

$$\Delta y \approx \frac{L}{d} \left(m + 1 + \frac{1}{2} \right) \lambda - \frac{L}{d} \left(m + \frac{1}{2} \right) \lambda$$

$$\Delta y \approx \frac{L}{d} m \lambda + \frac{L}{d} \lambda + \frac{L \lambda}{2d} - \frac{L}{d} m \lambda - \frac{L \lambda}{2d}$$

$$\Delta y = \frac{L \lambda}{d} \dots\dots(9.9)$$

Eq. (9.8) and eq. (9.9) show that bright and dark fringes are equally spaced.

Example 9.1

In Young double slit experiment, the distance between two slits is 0.25 cm. Interference fringes are formed on the screen placed at a distance of 1 m from the slits. The distance of the third dark fringes from the centre of screen is 0.059 cm. Find the wavelength of the incident light?

Solution:

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

$L = 1 \text{ m}$

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

For 3rd dark fringes, order $(m) = 2$

Wavelength $(\lambda) = ?$

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

$$\lambda = \frac{d y}{L \left(m + \frac{1}{2} \right)} = \frac{(2.5 \times 10^{-3}) \times (5.9 \times 10^{-4})}{1 \times \left(2 + \frac{1}{2} \right)} = 5.9 \times 10^{-7} \text{ m}$$

$$\lambda = 590 \text{ nm} \quad \because 1 \text{ nm} = 1 \times 10^{-9} \text{ m}$$

Example 9.2

Yellow sodium light of wavelength 589 nm is emitted by a single source and passes through two narrow slits 1 mm apart. The interference pattern is observed on a screen 225 cm away. How far apart are two adjacent bright fringes?

Solution:

We have

$$\lambda = 589 \text{ nm} = 589 \times 10^{-9} \text{ m} = 5.89 \times 10^{-7} \text{ m}$$

$$d = 1 \text{ mm} = 1 \times 10^{-3} \text{ m}$$

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

Width of fringes (Δy) = ?

$$\Delta Y = \frac{\lambda L}{d} = \frac{5.89 \times 10^{-7} \times 2.25}{1 \times 10^{-3}}$$

$$\Delta Y = 1.33 \times 10^{-3} \text{ m} = 1.33 \text{ mm}$$

The adjacent fringes will be 1.33 mm apart.

9.5 INTERFERENCE IN THIN FILMS

A thin film is a transparent medium whose thickness is very small. For example a thin layer of oil floating on water surface or a thin surface of soap bubble. It is a common observation that when light falls on these thin films of oil surface or soap bubble then we observe coloured patterns. This is due to the interference of reflected light from the two surfaces of thin film and it is explained under.

Consider a ray of light AB from a monochromatic source of wavelength ' λ ' that is allowed to fall on a transparent thin film of thickness ' d '. This incident ray is partially reflected from the upper surface of the film along BC and partially refracted into the transparent medium of film along BD. At point D, it is again reflected inside the medium along DE and then at point E, the ray refracted along EF as shown in Fig.9.9. Now these two rays BC and EF superimpose with each other in order to produce interference which is detected by our eyes.

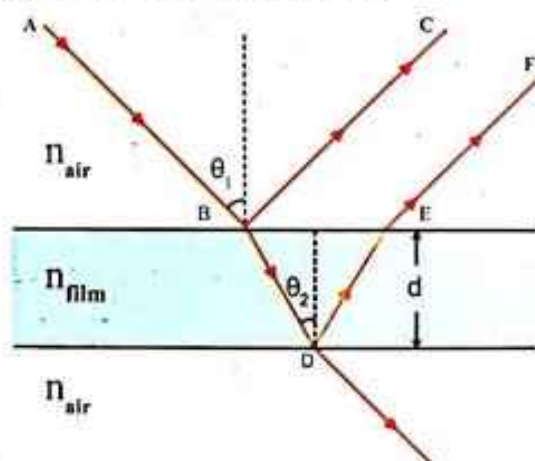


Fig.9.9: The incident ray is reflected from both upper surface and lower surface of thin film and interference is due to the superposition of these two reflected rays.

The Fig.9.9 shows that, the incident ray splits into two parallel reflected rays BC and EF. The distance covered by these two reflected rays are not same. The path difference between them depends upon angle of incident ray and thickness of the film. It is interesting to note that the point at which the path difference between two reflected rays is zero, a bright fringe should be formed but there is a dark fringe.

It is due to the fact that when the ray 'EF' is reflected from dense medium (film) to rare medium than there is an extra path difference of $\frac{\lambda}{2}$ added to it and due to this extra path difference the position of bright and dark fringes will be interchanged. Mathematically, it is explained as,

For bright fringes

$$\text{Path difference} = m\lambda + \frac{\lambda}{2}$$

$$\text{Path difference} = \left(m + \frac{1}{2}\right)\lambda \dots\dots(9.10)$$

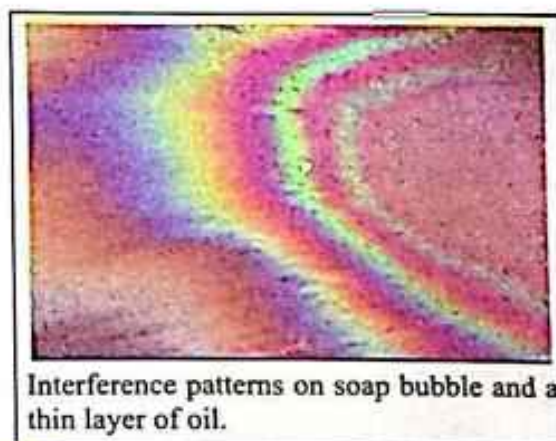
where $m = 0, 1, 2, 3, \dots\dots$

For dark fringes

$$\text{Path difference} = \left(m + \frac{1}{2}\right)\lambda - \frac{\lambda}{2}$$

$$\text{Path difference} = m\lambda \dots\dots(9.11)$$

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



Interference patterns on soap bubble and a thin layer of oil.

9.6 MICHELSON INTERFEROMETER

An interferometer is an optical instrument which is widely used to measure lengths or change in length with a great accuracy by means of interference fringes. It was introduced by American Physicists A.A. Michaelson in 1881. A schematic diagram of interferometer is shown in Fig. 9.10. It consists of a source of monochromatic light which is placed in front of a partially silver polished glass plate 'P', inclined at an angle of 45° to the horizontal. This plate is called beam splitter. There are also two highly polished mirrors M_1 and M_2 . The mirror M_1 is vertical and fixed. While the mirror M_2 is horizontal and adjustable. Another optical compensator glass plate P' same as 'P' is fixed between P and M_2 in order to eliminate the path difference between the two rays. To observe the interference pattern, a telescope is placed at the bottom in front of 'P' as shown in Fig. 9.10.

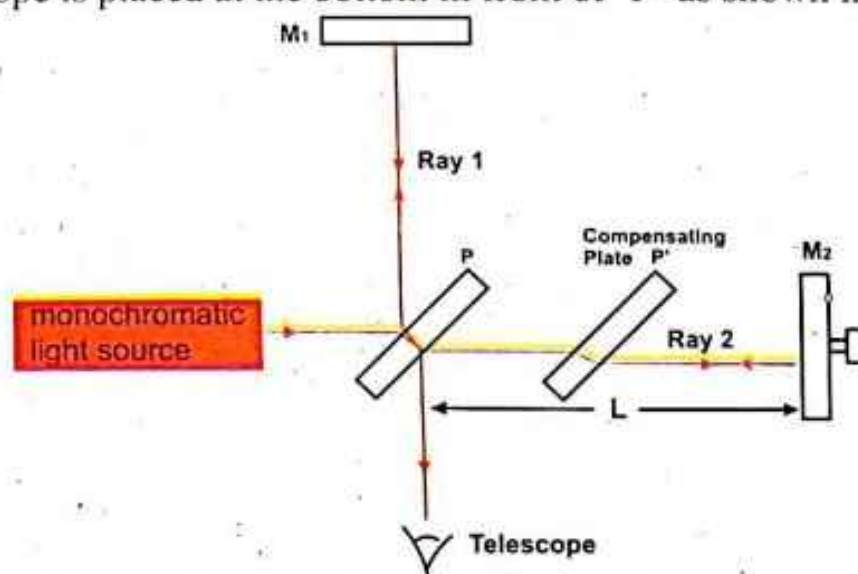


Fig.9.10: A schematic diagram of Michelson's Interferometer

The whole apparatus is mounted on rigid frame. When a ray of monochromatic light from a source is incident on the beam splitter 'P', it is partially reflected and partially refracted. The reflected ray (1) falls on a fixed mirror M_1 and

the refracted ray (2) pass through the compensator 'P' falls on moveable mirror M_2 . These two incident rays now reflected from mirrors M_1 and M_2 . The rays reflected from mirrors are again refracted and reflected from the plate 'P' and eventually recombine to produce an interference pattern which can be observed by the telescope.

The distance travelled by the two rays (1) and (2) is not same. There is a path difference between them. Hence we have interference pattern that consists of a series of bright and dark fringes. The numbers of these fringes that pass through a given point in certain time can be varied by adjusting the mirror M_2 .

Optically, there is also an extra path difference between the two rays due to the reflection and refraction of the rays from one medium to other and to eliminate this path difference the compensator has been used. Hence, the path difference between the two rays is made zero and we get first bright fringe. Similarly, to get the next bright fringe, M_2 is to be shifted at a distance $\frac{\lambda}{2}$. On this basis, a general relation can be obtained. If M_2 is shifted by a distance 'x', and 'm' numbers of bright fringes are obtained due to this shift then,

$$x = m \frac{\lambda}{2} \quad \dots\dots(9.12)$$

This is the fundamental relation of Michalson's interferometer where $m = 0, 1, 2, 3, \dots\dots$

Example 9.3

When the moveable mirror in the Michelson Interferometer is moved in one direction there are 400 fringes appear to pass through the field of view. If the light of wavelength 500 nm is used, then what is the distance through which the mirror has been moved?

Solution:

We have

Number of fringes = 400

Wavelength = $\lambda = 500 \text{ nm} = 500 \times 10^{-9} = 5 \times 10^{-7} \text{ m}$

Distance through which movable mirror is moved = $x = ?$

Equation of Michelson Interferometer $x = m \frac{\lambda}{2}$

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

$$x = \frac{400 \times 5 \times 10^{-7}}{2} = 1 \times 10^{-4} \text{ m}$$

$$x = 0.1 \text{ mm}$$

9.7 DIFFRACTION OF LIGHT

Similar to interference phenomenon, the diffraction phenomenon also supports the Huygens's wave theory of light. This phenomenon can be explained by an example of a small opaque ball which is placed between a source of light and a screen. Now when the ball is illuminated by light from a source, then we observed that its shadow is casted on a screen as shown in Fig. 9.11(a). The shadow is completely dark but it has bright spot at its centre and it gives the following two interesting results.

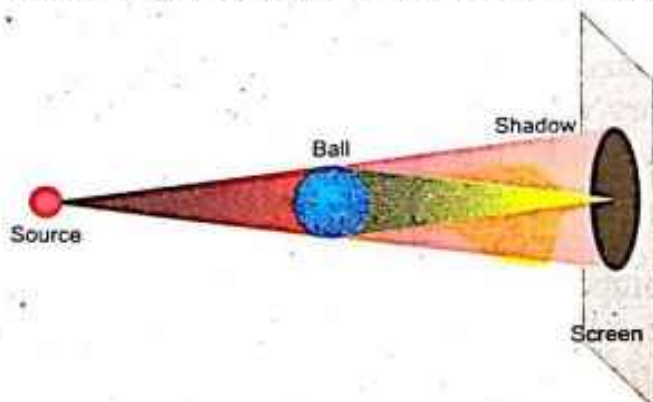


Fig.9.11(a): Experimental arrangement of diffraction of light

1. When light travels through an obstacle, it does not proceed exactly along a straight path but bends around the obstacle.
2. When the bending rays of light from the opposite sides of the obstacle are superimposed then there is bright spot at the centre due to the constructive interference.

This phenomenon of bending of light around the corners of an obstacle is called diffraction.

Similarly, when light passes through a narrow slit, the light also bends around the edges of the slit as shown in Fig. 9.11(b). When this bending of light is allowed to fall on the screen, a diffraction pattern which consists of bright and dark fringes is obtained on it. These results show that diffraction pattern depends upon the size of slit or obstacle. It may be pointed out that diffraction phenomenon will be observed only if the wavelength of the incident light is greater than that of the size of the slit. It means size of obstacle or width of slit should be comparable with the wavelength of light.



Fig.9.11(b): A diffraction pattern due to bending of light through edges of a narrow slit.

9.8 DIFFRACTION OF LIGHT DUE TO A SINGLE SLIT

To study the diffraction of light, a simple experiment can be demonstrated. The experimental setup consists of slit 'AB' of width 'd' which is illuminated by

beam i.e. parallel rays of monochromatic light from a source of wavelength ' λ '. A screen is placed parallel to the slit in order to observe the diffraction pattern on it, as shown in Fig. 9.12.

When beam of light is incident on slit AB in form of a primary wave front then according to Huygen, each point on the wave front at position of slit acts as a secondary source and produces secondary wavelets which propagate toward the screen.

When these secondary wavelets are superimposed at different points then it causes the formation of a diffraction pattern. Such pattern can be studied on the screen as shown in Fig. 9.12.

In order to determine the position of maxima and minima at the screen, we consider the points A, X, Q, Y and B along the width of slit such that the width of AQ, QB and XY is equal to $\frac{d}{2}$.

Thus, there is no path difference between the light waves from the points A and B or from X and Y.

When these rays are allowed to meet at the centre of the screen 'O', a bright fringe is formed at that point due to the constructive interference.

Similarly, we select another point 'P' at the screen below the point O such that the path difference between the waves

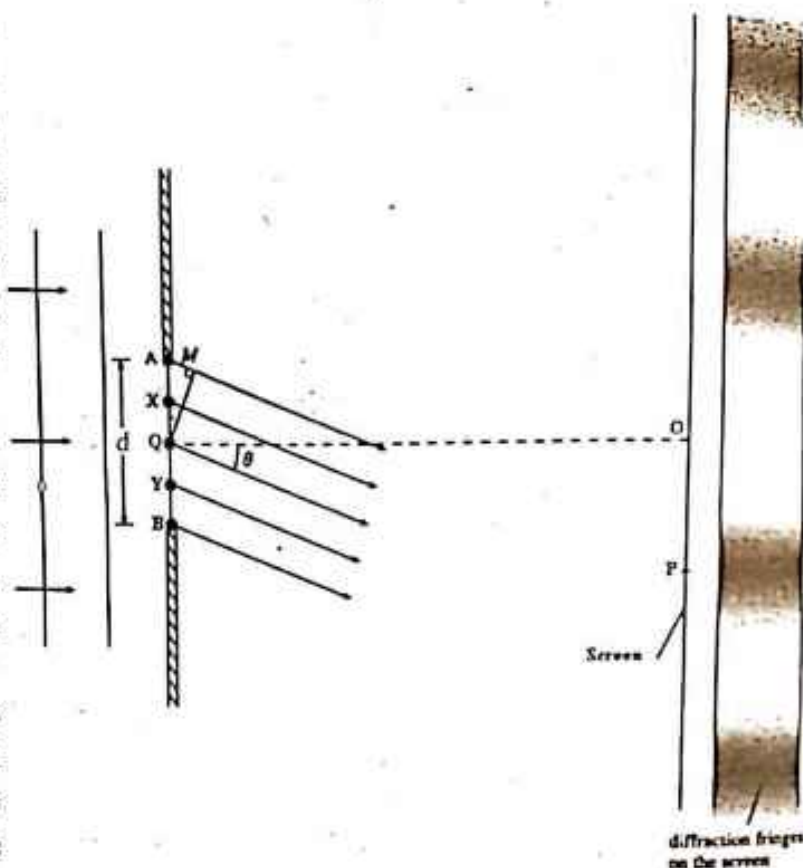


Fig.9.12: Diffraction of light through a single slit

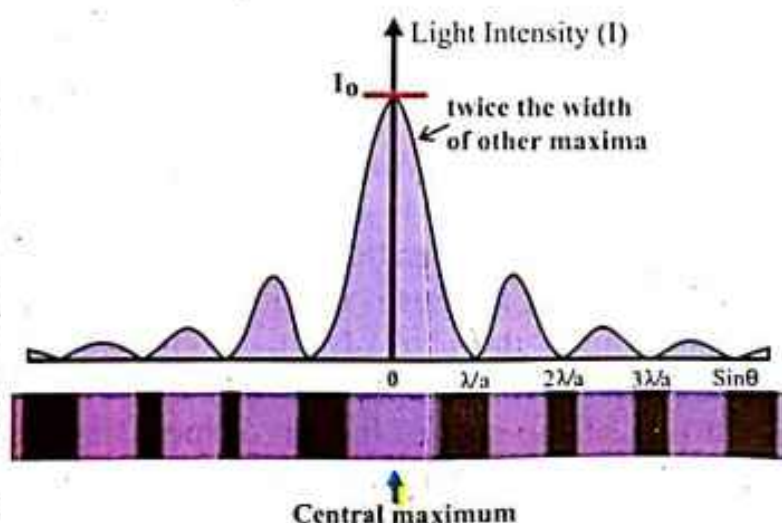


Fig.9.13: Diffraction pattern which consists of bright and dark fringes and it is obtained due to diffraction through a single slit

from the points A & B at the point P is λ but the path difference between the waves from the pairs of the points A & Q, X & Y and Q & B at the point P is $\frac{\lambda}{2}$.

Hence dark fringe is formed at the point P due to the destructive interference as shown in Fig. 9.13.

A general mathematical relation can be obtained if we take the a half section of slit AQ as $\frac{d}{2}$ and the path difference between the waves from the points A & Q as $\frac{\lambda}{2}$ which is equal to the points from A to M as shown in Fig. 9.12. Thus in triangle AQM

$$\frac{AM}{AQ} = \sin \theta$$

$$\left(\frac{\frac{\lambda}{2}}{\frac{d}{2}} \right) = \sin \theta$$

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

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

In general, the condition of 'm' orders of maxima on either side from the centre of the screen is given as;

$$d \sin \theta = m\lambda \dots\dots(9.1)$$

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

9.9 DIFFRACTION GRATING

A diffraction grating is a specially designed transparent glass plate which is used to study the diffraction phenomenon. It consists of a transparent glass slab which contains a large number of parallel and equidistance slits of same width separated by an opaque portion. The number of slits on the diffraction grating depends upon the wavelength of the incident light. For example, the wavelength of visible light is

POINT TO PONDER

How the fringes of interference are different than that of the diffraction?

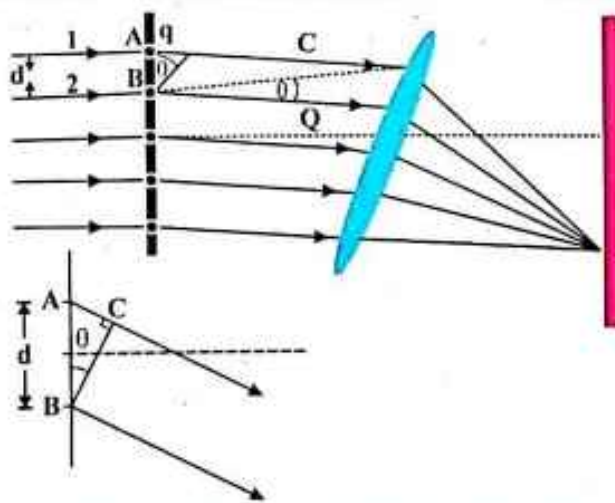
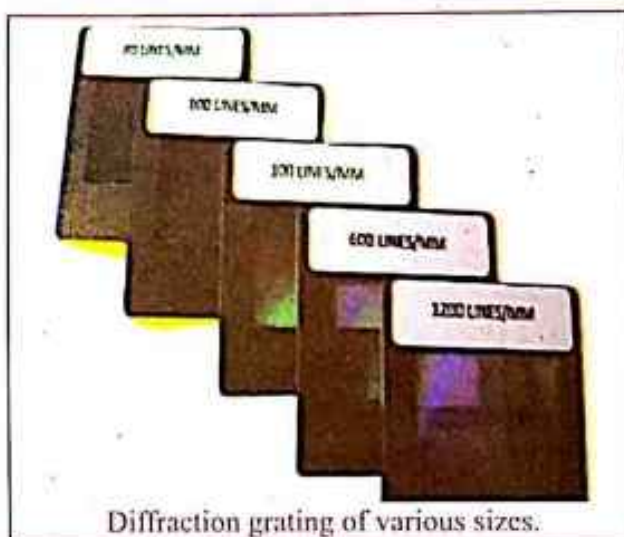


Fig.9.14: Diffraction phenomenon through a diffraction grating

400nm -700nm, it requires 4000 – 6000 lines per centimetre in order to observe diffraction effects by visible light. A typical slit width is given as;

$$d = \frac{1}{5000} \text{ cm} = 2 \times 10^{-6} \text{ m} = 2000 \text{ nm} \quad \because 1 \text{ nm} = 1 \times 10^{-9} \text{ m}$$

The parameter 'd' is called grating element. This example shows that if the size of slit is less than the wavelength of the incident light then the diffraction of the light could be observed.

Practically, the grating which contains too large number of slits can be made by using a diamond point (cutter) to scratch equally spaced grooves (slits) on a glass or metal surface. The opaque paste is used to dip the slab into it. Then it is etched from the surface and the paste remains inside the grooves, thus the lines are opaque lines and the transparent portions between them act as number of slits.

Consider parallel rays of light from a monochromatic source which are incident on a grating. These rays, in form of wave fronts, are passed through slits, such that each slit causes diffraction and the diffracted rays in turn interfere with one another to produce a pattern. This diffraction pattern is focused on the screen with the help of a convex lens as shown in Fig. 9.14. Let we take the two rays r_1 and r_2 , such that AC is a path difference between them as shown in Fig. 9.14.

In triangle ABC

$$\frac{AC}{AB} = \sin \theta$$

$$AC \text{ (path difference)} = d \sin \theta \dots\dots(9.14)$$

For constructive interference (bright fringes)

$$\text{Path difference} = m\lambda \dots\dots(9.15)$$

Comparing eq. 9.14 and eq. 9.15

$$d \sin \theta = m\lambda \dots\dots(9.16)$$

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

This is the basic relation of diffraction grating. Where 'm' is the order of fringe or image. For example, if all the diffracted rays are focused at $\theta = 0$ then, $m = 0$. This is called the zero order maximum. Similarly, if $m = 1$, $m = 2$ and so on then there will be bright images.

Example 9.4

The deviation of second order diffracted image formed by an optical grating having 5000 lines per centimetre is 32° . Calculate the wavelength of the light used.

Solution:

We have

$$\text{Order of diffraction} = m = 2$$

FOR YOUR INFORMATION

The first man-made diffraction grating was made around 1785 by American inventor **David Rittenhouse**, who stung hairs between two finely threaded screws. This was similar to notable German Physicist **Joseph von Fraunhofer's** wire diffraction grating.

FOR YOUR INFORMATION

Diffraction is maximum when the width of the opening is less than the wavelength of light.

Number of lines per centimetre = 5000 lines

$$\text{Grating element} = d = \frac{1}{N} = \frac{1}{5000} = 2 \times 10^{-4} \text{ cm} = 2 \times 10^{-6} \text{ m}$$

Angle = $\theta = 32^\circ$

Wavelength = $\lambda = ?$

Equation of diffraction grating $d \sin \theta = m\lambda$

$$\lambda = \frac{2 \times 10^{-6} \text{ m} \times \sin 32^\circ}{2} = 5.30 \times 10^{-7} \text{ m}$$

$$\lambda = 530 \text{ nm} \quad \because 1 \text{ nm} = 1 \times 10^{-9} \text{ m}$$

9.10 DIFFRACTION OF X-RAYS

X-rays are a type of electromagnetic waves with extremely short wavelength. Typical wavelength of x-rays is of the order of $1 \text{ \AA} (10^{-10} \text{ m})$. Therefore a grating which contains 5×10^7 numbers of slits per centimetre i.e. grating element of size $2 \text{ \AA} (2 \times 10^{-10} \text{ m})$ is required for diffraction of x-rays.

Practically, it is not possible to construct an optical grating of such too small size and large number of slits. To overcome this problem, W.H. Bragg and W.L. Bragg suggested the diffraction of x-rays can be observed by crystals. A crystal is an element whose atoms are arranged in a regular array and they are separated uniformly by a distance of the order of $2.15 \text{ \AA}$ or $2.15 \times 10^{-10} \text{ m}$. Therefore, the distance between two atoms can act as a slit. The diffraction of X-rays takes place when these are allowed to fall on the crystal. Consider two monochromatic rays which are incident on a crystal at angle ' θ ' with the surface of crystal which is called glancing angle. Let these two rays be reflected from the 1st two planes of atoms separated by a distance ' d '. A schematic diagram in Fig. 9.15 shows that the ray reflected from the lower plane travels farther than the ray reflected from the upper plane. The path difference between these two reflected rays is given as,

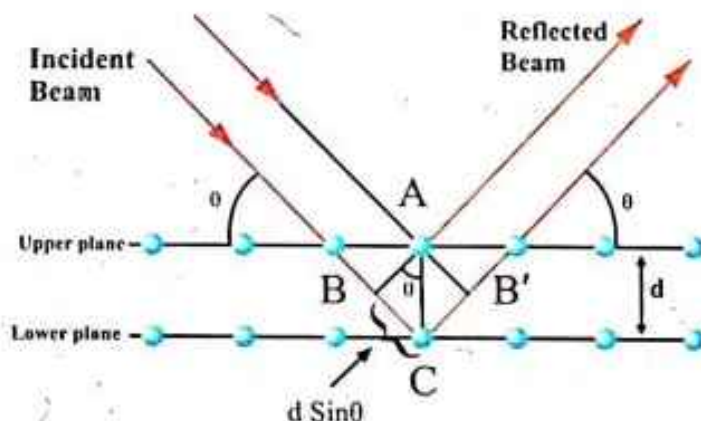


Fig.9.15: A schematic arrangement for diffraction of x-rays by a crystal.

FOR YOUR INFORMATION

You can produce single slit diffraction by holding the index and middle fingers of one hand together and looking at a bright light through the space between them. Then press the fingers together to change the opening size and observe how the diffraction pattern changes.

$$\text{Path difference} = BC + CB' \dots\dots(9.17)$$

In triangle BAC

$$\frac{BC}{AC} = \sin \theta$$

$$BC = AC \sin \theta \quad \because AC = d$$

$$BC = d \sin \theta \quad \dots\dots(9.18)$$

Similarly from triangle B'AC,

$$CB' = d \sin \theta \quad \dots\dots(9.19)$$

Putting the values of eq. (9.18) and eq. (9.19) in eq. (9.17)

$$\text{Path difference} = d \sin \theta + d \sin \theta$$

$$\text{Path difference} = 2d \sin \theta \quad \dots\dots(9.20)$$

For bright images (Constructive interference)

$$\text{Path difference} = m \lambda \quad \dots\dots(9.21)$$

Comparing eq. (9.20) and eq. (9.21)

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

This is a Bragg's law, where $m = 1, 2, 3, 4, \dots$

Example 9.5

How far apart are the diffracting planes in a NaCl crystal for which x-rays of wavelength $1.54 \text{ \AA}$ makes a glancing angle 16° in the first order?

Solution:

We have

Distance between two planes = $d = ?$

$\lambda = \text{Wavelength of incident x-rays} = 1.54 \text{ \AA}$

$$\lambda = 1.54 \times 10^{-10} \text{ m}$$

Glancing angle = 16°

Order of image = $m = 1$

According to Bragg's Law

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

$$d = (1) (1.54 \times 10^{-10}) / 2 \sin 16^\circ$$

$$d = 2.79 \times 10^{-10} \text{ m} = 2.79 \text{ \AA}$$

9.11 POLARIZATION

Wave nature of light has been verified by the interference and diffraction. However, these phenomena cannot explain the transverse or longitudinal behaviour of light wave. For this purpose, the polarization phenomenon is used. Polarization is a property that exhibits only for a transverse wave. It is explained by an example.

Consider a string which is passed through two parallel rectangular slits. When the string is vibrated up and down, a transverse wave which consists of crests and troughs propagate along the string.

If the two slits are also parallel to the vibration of string, then wave is passed through both slits and each part of the string vibrates freely in the slits. The amplitude is not affected as shown in Fig. 9.16. This is a mechanical transverse polarized wave. However, if one slit is rotated by 90° in its plane, the slit will point along the horizontal plane. As the wave arrives at second the slit, the part of string tries to move vertically but the contact force by the horizontal slit does not allow it. Then wave does not pass through it. This shows that the incident wave is transverse wave. In case of longitudinal periodic wave along a stretched string, the wave will not be affected by the rotation of slit. This idea helps us in the explanation of transverse wave nature of light.

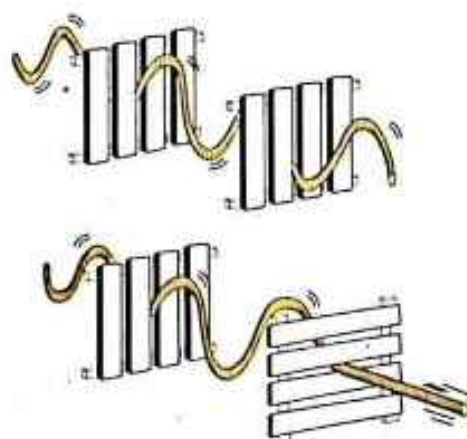


Fig.9.16: Polarization phenomenon due to string and slits arrangement.

Light waves are electromagnetic in nature. An electromagnetic wave consists of electric and magnetic field vectors which are vibrating at right angle to each other. The ordinary light is three dimensional and its components are vibrating in all direction. Therefore, it is called unpolarized light. However, when the vibration of light is restricted only in one plane then such light is called polarized light or plane polarized light.

9.11.1 Production and detection of plane polarized light

The ordinary light by lamp, bulb or the sun is unpolarized because its components are vibrating in all directions. When all the vibrating components are removed except those having vibration along the unidirection plane then it is called plane polarization. It can be achieved by various methods such as selective absorption, reflection, refraction from different surfaces and scattering by small particles.

The selective absorption is being used at large scale to obtain plane polarized light by using a device known as "Polaroid". It was introduced by two American Scientists E.H. Land and Boston. It consists of a transparent sheet of nitrocellulose which has embedded special needle-like crystal of herapathite and it has transmission axis. Thus, the Polaroid transmits those light waves whose electric field vector vibrates parallel to the polarizing direction.

Consider unpolarized light of intensity ' I ' from a source which is incident on the Polaroid sheet (P_1), those electric field vectors which are parallel to the axis of transmission are passed through Polaroid (P_1) while the remaining electric field vectors are absorbed by the Polaroid sheet. In output, we have the plane polarized light whose intensity is less than the original unpolarized light waves.

In order to confirm whether the light has been polarized, we introduce another Polaroid ' P_2 ' same as that of ' P_1 ' but perpendicular in direction to that of P_1 as shown in Fig.9.17.

It is being used as analyzer now when the transmission axes of ' P_1 ' and ' P_2 ' are parallel, then the intensity of polarized light from both ' P_1 ' and ' P_2 ' is same.

When the analyzer P_2 is rotated such that the transmission axes of P_1 and ' P_2 ' are perpendicular then no light will be transmitted through the analyzer ' P_2 '. Thus, this result has confirmed that light waves are transverse. If it were longitudinal, then light would not disappear by the rotation of the analyzer ' P_2 '.

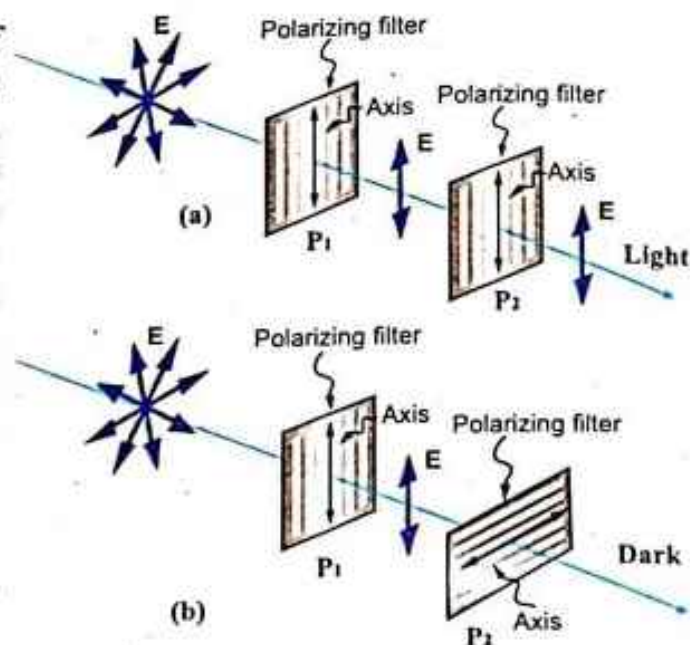


Fig.9.17: Polarization of light through polarizers.
(a) Unidirectional light pass through both polarizers
(b) Unidirectional light pass through only one polarizers

POINT TO PONDER

Why the reflected light from surface of water or a mirror cost unpleasant effect in our eyes?

SUMMARY

- **Nature of light:** The light has a dual nature that is Newton defined it in terms of corpuscle while Huygen defined it in terms of wave.
- **Wave front:** The surface on which all the particles vibrate in the same phase and have same displacement from the source is called wave front. When the medium is homogenous then spherical wave fronts are propagated outward from the source.
- **Huygen's Principle:** According to Huygen's principle, each point on the wave front is being considered as the secondary source that produces secondary wavelets.

- **Coherent and monochromatic waves:** The waves which have same frequency with zero phase or constant phase difference are known as coherent waves and the waves which have single wavelength are known as monochromatic waves.
- **Interference:** When two or more coherent waves are superimposed then the amplitude of the resultant wave is increased or decreased and as a result bright and dark fringe are obtained. This phenomenon is known as interference of light.
- **Young's double slits experiment:** The result of Young's double slit experiment is a proof of Huygen's wave theory of light. According to this experiment the position of bright and dark fringe at the screen are given as;

For bright fringes, $d \sin \theta = m\lambda$

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

Fringe spacing between two successive bright and dark fringes is given as

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

- **Thin film:** A thin film is a transparent medium with thickness comparable with the wavelength of light falling on it. Due to an extra path difference, the position of bright and dark fringes is interchanged in thin film.
- **Interferometry:** It is the technique of diagnosing the properties of two or more waves by studying the pattern of interference created by their superposition.
- **Interferometer:** The instrument used to interfere the waves together is called an interferometer.
- **Michelson interferometer:** It is an optical instrument which is used to measure extremely small distance with high precision using interference phenomenon.
- **Diffraction:** Bending of light through edges of slit is known as diffraction.
- **Diffraction grating:** A diffraction grating is a specially designed transparent glass plate which is used to study the diffraction phenomenon. A mathematical relation for diffraction grating is given as $d \sin \theta = m\lambda$
- **X-ray Diffraction:** X-rays have shorter wavelength and these can be diffracted by a crystal, where the inter atomic distance between two atoms acts as slit. Bragg's law for x-ray diffraction is given as $2d \sin \theta = m\lambda$

- **Polarization:** The confinement of beam of light in a given direction or plane is called polarization of light. This phenomenon proves that the nature of light is transverse.
- **Polarized light:** A light wave in which its electric field vectors are vibrating in unidirectional is known as polarized light. Polarization phenomenon proves that the nature of light is transverse.

EXERCISE

○ Multiple choice questions.

1. Who presented the corpuscular theory of light?
(a) Huygen (b) Newton (c) Young (d) Maxwell
2. Which phenomenon does not explain the of wave theory of light?
(a) Polarization (b) Interference (c) Diffraction (d) Compton effect
3. Interference of light occurs when the source of light are;
(a) Monochromatic (b) Coherent
(c) Closed to each other (d) All of these
4. In Young's double slit experiment, if the distance between two slits is halved and distance between slits and screen is doubled then what will be the fringe width?
(a) Remain same (b) Halved (c) Doubled (d) Quadrupled
5. In Young's double slit experiment, the ratio of fringe width of bright to dark fringe is;
(a) 1:1 (b) 1:2 (c) 2:1 (d) 2:3
6. In the Young's double slit experiment if white light is used then;
(a) Bright fringes will be seen
(b) Dark fringes will be seen
(c) Alternate dark and bright fringes will be seen
(d) No interference fringes will be seen
7. When light is reflected from dense medium to rare medium then its path difference.
(a) Remains same (b) Changes by $\left(\frac{\lambda}{2}\right)$
(c) Changes by λ (d) Changes by $\frac{3\lambda}{2}$
8. Michelson interferometer is an optical instrument which is being used for the measurement of;
(a) Velocity (b) Frequency (c) Amplitude (d) Wavelength

9. Mathematical condition of destructive interference in thin film is;
 (a) $m\lambda$ (b) $\frac{m\lambda}{2}$ (c) $\left(m + \frac{1}{2}\right)\lambda$ (d) $(m + \lambda)$
10. Which parameter of light does not change when light is reflected from dense medium to rare medium?
 (a) Frequency (b) Wavelength (c) Velocity (d) Amplitude
11. In Michelson interferometer, a fringe is changed by changing the position of movable mirror at a distance
 (a) $\frac{\lambda}{4}$ (b) $\frac{\lambda}{2}$ (c) λ (d) 2λ
12. Number of slits in a diffraction grating depends upon.
 (a) Speed of light (b) Frequency of light
 (c) Wavelength of light (d) Amplitude of light
13. If the wavelength of the incident x-rays is 2×10^{-10} m then the required number of slits per centimetre for its diffraction should be
 (a) 5×10^6 (b) 5×10^7 (c) 5×10^8 (d) 5×10^{10}
14. Which phenomenon has confirmed that light is transverse wave?
 (a) Interference (b) Diffraction (c) Reflection (d) Polarization
15. If the unpolarized incident light with intensity 'I' is polarized by a Polaroid sheet, then the intensity of plane polarized light will be;
 (a) $\frac{I}{2}$ (b) $\sqrt{I}$ (c) I (d) 2I
16. Which one of the following cannot be polarized.
 (a) X-rays (b) Radio waves
 (c) Ultraviolet waves (d) Sound waves

SHORT QUESTIONS

- How can you define light?
- Does the ether exist as proposed by Huygen for wave theory?
- Under what condition, the spherical wave fronts are formed?
- What is Huygen's principle?
- What are the conditions for interference of light?
- How coloured fringes are obtained on soap bubble?
- How many phenomena are there in the favour of wave theory of light?

8. What is the cause of changing the position of bright and dark fringes in interference by thin film?
9. What is the difference between interference and diffraction?
10. How diffraction pattern is obtained on the screen by using principle of superposition?
11. Why diffraction of x-rays is possible only by a crystal?
12. What are Polaroid and polarizer?
13. How can polarized light be detected?
14. Can visible light produce interference fringes?
15. In the Young's double slit 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?
16. State whether the fringe width for bright and dark fringes in Young's interference is always constant?
17. Find the grating element of the diffraction grating containing 2000 lines/cm?

COMPREHENSIVE QUESTIONS

1. What is meant by wave front? Under what conditions the spherical and plane wave fronts are formed.
2. What is the Huygens's principle? Explain that how can you obtain the secondary wave front by the primary wave front.
3. State and explain the Young's double experiment for the interference of light. Also discuss the position and width of bright and dark fringes.
4. Explain the interference phenomenon in thin film and derive its mathematical formula for a constructive and destructive interference.
5. State and explain Michelson interferometer and its working principle in the determination of wavelength of bright fringes.
6. What is diffraction of light? Explain the diffraction of light due to a single slit.
7. State and explain diffraction grating and its working principle.
8. Discuss the diffraction of x-rays by a crystal and explain Bragg's law.
9. What do you know about the polarization? State and explain the production and detection of polarization of light.

NUMERICAL PROBLEMS

1. Light of wavelength 400 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? (0.11°, 0.8mm)

2. In a double slit interference experiment, the distance between the slits is 2 mm and the fringe spacing is 0.45 mm on a screen which is 200 cm away from the slits. Find the wavelength of the light. (450 nm)
3. Interference fringes were produced by two slits, spaced 0.2 mm apart, on a screen at a distance of 150 cm from the slits. The third bright fringe is found to be displaced 7.5 mm from the central fringes. What is the wavelength of light producing the fringes? (333 nm)
4. Green light of wavelength 540 nm is diffracted by grating having 2000 lines/cm. (a) Compute the angular deviation of the third order image. (b) Is 12th order image possible? (18.9°, impossible)
5. Sodium light of wavelength 590 nm is incident normally on a grating having 600 lines per millimetre. What is the highest order of the spectrum obtained with the grating? (2)
6. How many fringes will pass a reference point if the moveable mirror of Michelson's interferometer is moved through a distance 0.07 mm using light of wavelength 580 nm? (241)
7. In a Michelson interferometer, 100 fringes cross the field of view when the movable mirror is displaced by 0.02948 mm, calculate the wavelength of the monochromatic source. (5896 Å)
8. Calculate the distance through which the mirror of the Michelson interferometer has to be displaced between two consecutive positions of maximum distinctness of D₁ and D₂ lines of sodium. Wavelength of D₁ line is 5890Å and of D₂ line is 5896Å. (0.2894 mm)
9. X-rays of wavelength 1.50 nm are observed to undergo a second order reflection at a Bragg's angle of 15° from a quartz (SiO₂) crystal. What is the interplanar spacing of the reflecting planes in the crystal? (5.79 nm)