Unit 9 PHYSICAL OPTICS

The colours reflected by this butterfly wings vary with angle, why?

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 that it provides to support the wave theory of light.
- Explain colour pattern due to interference in thin films.
- Describe the parts and working of Michelson interferometer and its uses.
- Explain diffraction and identify that interference occurs between waves

- 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.

Interference and diffraction are two phenomena most easily understood in terms of the propagation of light as a wave. Interference of light occurs when two or more light sources are superimposed. Diffraction of light occurs when part of its wave-front is obstructed (e.g., by a narrow slit). Diffraction is treated qualitatively as a precursor to a more extended quantitative treatment of the interference of light from two slits. This is extended to the transmission through diffraction grating. Polarization which establishes transverse nature of light waves along with its applications have also been discussed in this unit.

FOR YOUR INFORMATION

The study of properties and nature of light had been an active field of research since Ibnal Haitham's time 945 A.D. For the first time a Muslim scientist Alhozen studied the phenomena of reflection and refraction of light on scientific grounds. He discovered the laws of reflection and also studied the refraction of light. He recognized that the angle of incidence and the angle of refraction were related, but was unable to discover the relation between them.

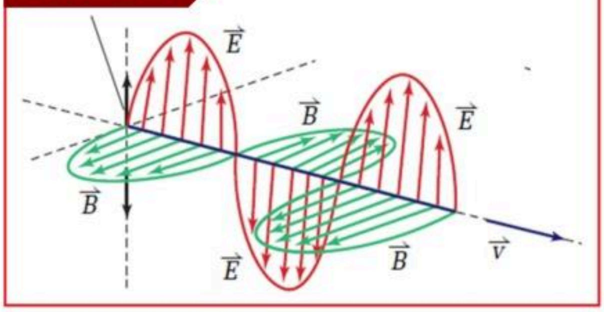
9.1 NATURE OF LIGHT

The most important development about the nature of light was the work of Maxwell. In 1873 he showed that the light is a form of high frequency electromagnetic waves. The electric and magnetic field vectors are oscillating perpendicular to the direction of propagation of the waves.

This theory predicts that these waves should have a velocity of about 3×10^{8} ms^{-1}. These waves do not require any medium for their propagation.

Presently we believe that the nature of light is dual. In case of reflection, rarefaction, diffraction, interference and polarization, light behave like waves, while in case of photoelectric effect and Compton shift it behaves like particle.

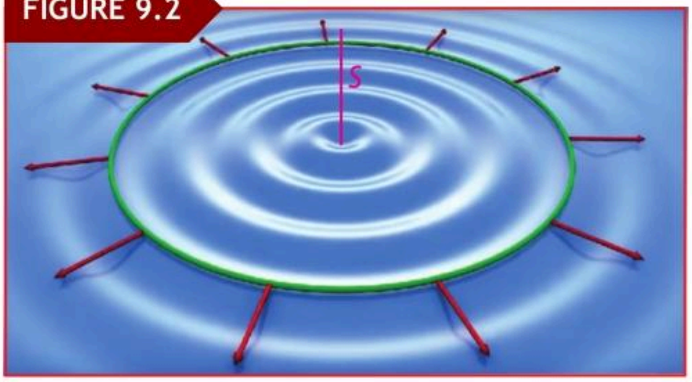
FIGURE 9.1



9.2 WAVE FRONT

Whenever a wave passes through a certain medium, its particles are disturbed and execute simple harmonic motion. For example when a small stone is dropped into a pond of still water, a series of circular crests appears which move out from the point where the stone hits the water surface.

FIGURE 9.2



All points lying on a crest are in the same state of vibration and have the same phase.

The locus of all the points in a medium which have the same phase is known as a wavefront. Now consider a point source of light *S*, as in Figure 9.2. The waves emitted from this source propagate outwards in all directions with speed *c*. Since in optics we deal with the waves traveling through space in three dimensions. Hence in case of point source of light in a certain homogeneous medium, the wave fronts will be concentric spheres, with centers at the source S. *A portion of the spherical wave is called a circular wavefront.*

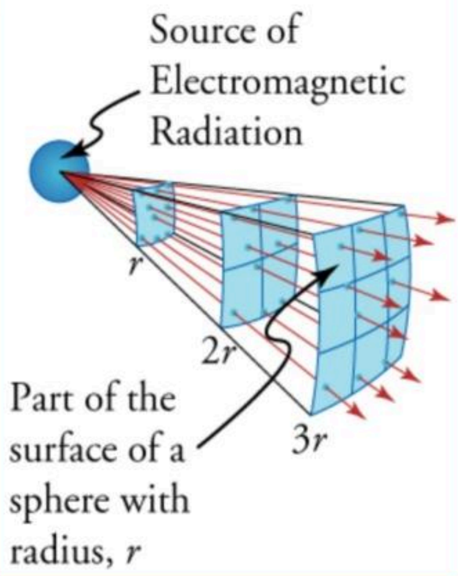
These spherical waves travel outward from the source. To indicate the direction of propagation of the wave fronts, arrows are drawn from the source. *The arrows to indicate the direction of wavefronts are called rays.*

The rays are always perpendicular to the wave fronts Figure 9.3. Hence we can specify the motion of a wave either by the use of rays or by drawing the wave itself.

The illuminance varies inversely with the square of the distance from a source of light as shown in Figure .9.3.

As the wave travels from the source, its curvature decreases, at a very large distance a small portion of a spherical wave front will become nearly plane surface. *This straight portion of a special wavefront is known plane wave front.*

FIGURE 9.3



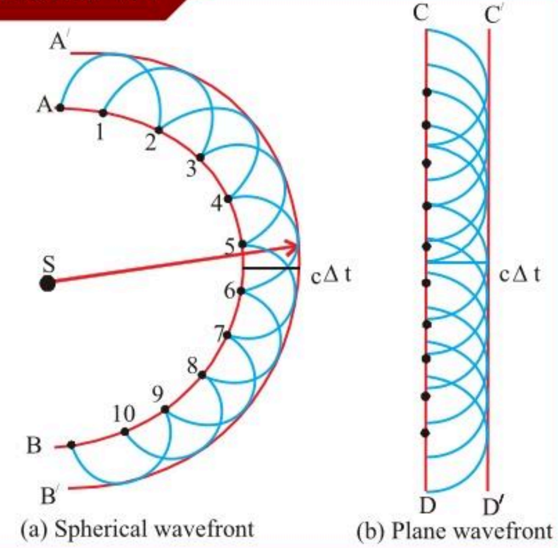
9.3 HUYGEN'S PRINCIPLE

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

The first part of the Huygen principle state that "every point of a wave front may be considered as a source of secondary spherical wavelet, which spread out in forward direction with a speed equal to the speed of propagation of the wave".

The second part of the principle state that "The new position of the wave front after time "$t + \Delta t$" can be found by drawing a plane tangential to all the secondary wavelets. We shall

FIGURE 9.4



(a) Spherical wavefront (b) Plane wavefront illustrate this principle by an example shown in the Figure 9.4.

Here AB represents the position of a spherical wave front at a particular instant of time *"t"*, due to the source *"S"*. We are required to determine the new position and shape of the wave front AB after time "$t + \Delta t$". According to Huygen's principle in first part we take several point represented by dots 1,2,3,….10 on the wave front AB which serve as the sources of secondary wavelets. The spherical waves emitted from these points are shown by drawing hemispheres of radius "$c \Delta t$" where *"c"* is the speed of light.

According to 2nd part of Huygen principle we draw a surface $A'B'$ which is tangent to all the secondary wavelets. Thus $A'B'$ is the new position of the wave front after time "Δt" as in Figure 9.4 a.

Similarly if we have a plane wave front in a medium, we can find the new position of that plane wave front after certain time by applying Huygen principle, as shown in Figure 9.4 b.

9.4 COHERENT SOURCES

The sources which produce waves having the same frequency, equal or comparable amplitude and a constant phase difference are called coherent sources.

Our most important source of light and life sustaining radiation is the sun. The most artificial sources of light are the hot bodies which radiate light and infrared radiation. Thus each source of light emits a very large number of waves with random phases. Because in a light source the phase is constantly changes, as light is emitted in short bursts when electrons in individual atom suffer energy changes that occur very quickly and randomly. Phase changes occur abruptly when different atoms come in to action. This is true for light coming from different parts of the same source except laser. To get two coherent waves from a point source, one of the following two methods is adopted.

i. Division of wavelength, as in Young's double slits, Fresnl's byprism and Lioyld's mirror.

ii. Division of amplitude by partial reflection and transmission at a boundary as in Newton's rings.

Do You Know?

Monochromatic or single colour light is specified by a single wavelength. It is very difficult to get a truly monochromatic source of light. However using filters one can get a source which gives light within a narrow band of wavelength.

9.5 INTERFERENCE OF LIGHT

Interference is described as *the effect produced by the superposition of waves from two coherent sources passing through the same region.*

When two waves of light having the same frequency, amplitude and a constant phase relationship are propagating through a certain region of space in the same direction. They reinforce each other at some points while cancel the effect of each other at the other points. This phenomena of superposition of light waves is called interference of light. The experimental demonstration of the interference of light waves was not successfully performed by scientists before Thomas Young, because the sources of light used were not coherent.

Conditions to observe Interference of light

The following conditions are required for the interference of light waves: -

i. The light waves must come from two coherent sources.
ii. The amplitude of the waves must be equal or nearly equal.
iii. The light waves should be perfectly monochromatic.
iv. The path difference of the waves from the two sources must be small.
v. The principle of linear superposition should be applicable.

To observe interference effects of light we place a screen at some distance from the two coherent light sources as shown in the Figure 9.5.

Quiz:

Young's double slit experiment breaks a single light beam into two sources. Would the same pattern be obtained for two independent sources of light, such as the headlights of a distant car?

Example 9.1 SODIUM VAPOUR

Yellow light from a sodium vapour lamp of wavelength 5893×10^{-10} m is directed upon two narrow slits 0.10 cm apart of the Young's experiment. Find the position of the first bright and dark fringes on a screen 100 cm away.

GIVEN

Wavelength of light $= \lambda = 5893 \times 10^{-10}$ m

separation of slits $= d = 0.10$ cm $= 0.001$ m

distance of slits from the screen $= L = 100$ cm $= 1$m

order of the fringe $= m = 1$

REQUIRED

position of the 1st bright fringe $= y_{bright} = ?$

position of the 1st dark fringe $= y_{dark} = ?$

SOLUTION

(a), As for the bright fringe is

$$y_{bright} = L\frac{\lambda}{d}$$

$$y_{bright} = \frac{1 \times 5893 \times 10^{-10}}{0.001} = 5.893 \times 10^{-4} \text{ m}$$

(b) And for the dark fringe is

$$y_{dark} = L\frac{\lambda}{2d} = \frac{1 \times 5893 \times 10^{-10}}{2 \times 0.001}$$

$$y_{dark} = 2.953 \times 10^{-4} \text{ m.}$$

2.953×10^{-4} m. **Answer**

Example 9.2 **YOUNG'S INTEFERENCE**

Light of wave length 546 nm produces Young's interference pattern. The second order dark fringe is along the direction that makes an angle of 18 min, related to the direction to the central maximum. What is the distance between the slits?

GIVEN

Wavelength of light = λ = 546 n m = 546×10^{-9}m

Order of dark fringe = m = 2.

Angle = θ = 18 min = $\frac{18}{60} = 0.30^0$ (As 1^0 = 60 minutes)

REQUIRED

distance between the slits = d = ?

SOLUTION

For mth dark fringe , we know that

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

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

$$d = \left(2 + \frac{1}{2}\right) \times \frac{546 \times 10^{-9}}{\sin 0.3^0}$$

$$d = 2.5 \times \frac{546 \times 10^{-9}}{5.236 \times 10^{-3}}$$

$$d = 260.7 \times 10^{-9} \times 10^{3}$$

$$d = 260.7 \times 10^{-6}\text{m} = \boxed{260.7\ \mu\text{m}}$$ **Answer**

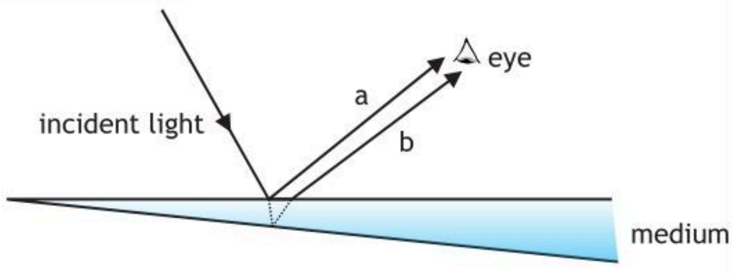
Assignment 9.1:

The **3rd** bright fringe in a double slit experiment makes a 2.4° angle with respect to the central line. The wavelength of the monochromatic light used is 480nm. Find the distance ***d*** between the two sources. (0.0344mm)

9.7 INTERFERENCE IN THIN FILM

You may have seen the bands of colour which occurs on the upper surface of a slightly oily water. Similarly colours are observed in the soap bubbles on the surface of water. These colour bands are really interference fringes caused by the rays reflected from the upper and lower surfaces of a thin film of oil on water.

FIGURE 9.11



The principle of interference through a thin film is based on the division of amplitude, by using partial reflection and transmission at the boundary of the two media.

Now let us see how these interference bands of colour are produced. Consider a thin film of a refracting medium with a thin wedge shaped structure and refractive index as shown in the Figure 9.11.

A beam of monochromatic light of wavelength "λ" is incident on this thin film. This beam of light is splitted in to two parts. Part *"a"* is reflected from the upper surface and part *"b"* is reflected from the lower surface of the film. As the film is thin, so the separation between the parts *a* and *b* is very small. Moreover the two rays *a* & *b* are being the parts of the same beam, will have phase coherence and superpose each other. It can be seen that the path of ray b is longer than the ray a. Their path difference will actually depend upon , (i) thickness and nature of the film and (ii) the angle of incidence.

(a). When a wave travels from a medium of lower refractive index to a medium of higher refractive index, it under goes a phase change of 180° (π rad) after reflection.

(b). There will no phase change in the reflected wave if it travels from a medium of higher refractive index to a lower refractive index.

Do You Know?

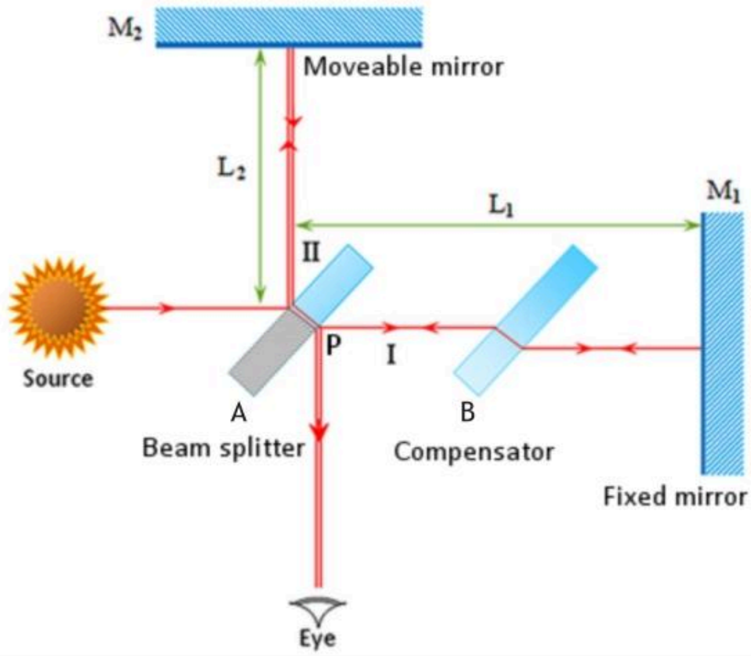
Different colours can be seen on the soap bubble whenever the light of the sun is falling on its surface.

When white light is incident on a thin film of irregular thickness at all possible angles, we shall observe the interference pattern due to each spectral colour separately. This is possible that at certain place on the film its thickness and the angle of incidence of light are such that the condition of destructive interference of one colour is being satisfied. Hence this portion of the film will exhibit the remaining colours of the white light, because the different wavelength reinforce at different places. As a result highly coloured fringes are observed and we have the rainbow effect for soap bubbles and oil film on the surface of water.

9.8 MICHELSON'S INTERFEROMETER

Michelson Interferometer is an optical instrument. It is used to study the interference of light waves and find its wavelength. The principle of Michelson interferometer is based on the division of amplitude, usually by partial reflection and transmission of light at the boundary of the two medium. The essential parts of the interferometer, devised by Michelson are the two plane mirror M_1 & M_2 and two glass plates *"A & B"* arranged as shown in the Figure 9.12 (a). The plate *"A"* is lightly silvered on the back, so that light which falls on that surface, half is reflected and half is transmitted. The mirror M_1 is moveable while the mirror M_2 is fixed.

FIGURE 9.12 (a)



ray diagram of Michelson interferometer

A beam of monochromatic light from the source *"S"* falls on the plate *"A"*, where it is splitted in to two parts. The first part is reflected from plate *"A"* moves towards the mirror *"M_1"*. After reflection from the mirror *"M_1"*, this part transmits through the plate *"A"* and enters the eye through the telescope. The second part of the light transmits through the plate *"A"* and moves towards the mirror M_2. After reflecting from there, this ray comes to the plate *"A"* from which it is again reflected and enters the eye. The plate B is introduced in path of beam II as an compensator plate to equalize the path length of beam and II in glass.

Conditions for interference

If the path difference between the two parts of light is either zero or integral multiple of wavelength "λ" then constructive interference will takes place and brightness will be observed.

$$d = 0, \lambda, 2\lambda, 3\lambda \ldots\ldots\ldots\ldots$$

$$d = m\lambda$$

Where $m = 0,1,2,3\ldots\ldots\ldots\ldots\ldots$

But if the path difference between the two parts of light is odd integral multiple of half wavelength then destructive interference will occur and darkness will be seen

$$d = \frac{\lambda}{2}, \frac{3\lambda}{2}, \frac{5\lambda}{2} \ldots\ldots\ldots\ldots$$

$$d = (m + \frac{1}{2})\lambda$$

Where m = 0,1,2,3................

Let the two mirrors "M_1" and "M_2" are at equidistance from plate "*A*", so the two beams travel optically similar path. Here plate "*B*" is used to introduce the same retardation in beam "2" as introduced in beam "1" by its two passages through plate "*A*". So the path difference between the two beams of light is zero and bright fringe is observed, due to constructive interference.

Alternate Bright And Dark Fringes

Now if the mirror "M_1" is moved through a distance $\lambda/4$ backward, then the path difference between the two beams will be equal to $\lambda/2$ and dark fringe will be seen. When the mirror "M_1" is further moved through distance $\lambda/4$ then the path difference will become "λ" and now bright band will be observed Figure 9.12 (b). Thus as the mirror "M_1" is moved slowly through distance $\lambda/4$ each time, bright and dark fringes will appear alternately.

FIGURE 9.12 (b)

Fringes produced with a Michelson interferometer.

Wavelength of light

To find the wavelength λ of light used, let m number of fringes are observed, when the mirror M_1 is moved backward through distance $\frac{\lambda}{4}$ each time. Then the total distance P is

$$P = m\left(\frac{\lambda}{4} + \frac{\lambda}{4}\right)$$

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

$$\lambda = \frac{2P}{m} \qquad (9.9)$$

Knowing the value of m and P we can find λ.

Example 9.3 **SODIUM VAPOUR**

A red laser light of wavelength 630 nm is used in a Michelson interferometer. While keeping the mirror M1 fixed, mirror M2 is moved. The fringes are found to move past a fixed cross-hair in the viewer. Find the distance the mirror M2 is moved for a single fringe to move past the reference line.

GIVEN

wavelength = 630 nm,
for single fringe crossing m= 1

REQUIRED

The distance traveled by M_2=?

SOLUTION

For a 630-nm red laser light, and for each fringe crossing (m=1), the distance traveled by M_2 if you keep M_1 fixed is

$$P = \frac{m\lambda}{2} = \frac{1\times 630}{2}\text{nm} = 315\text{nm}$$

$P = 315$nm **Answer**

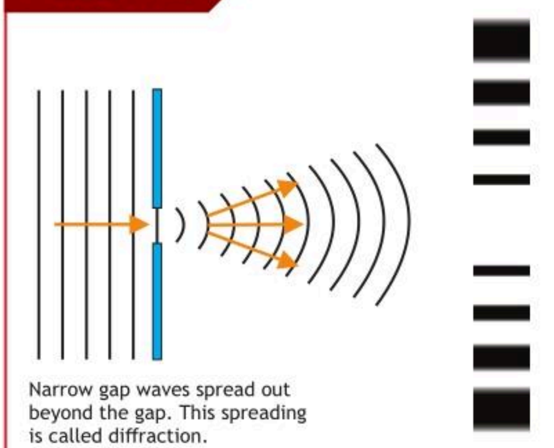
9.9 DIFFRACTION OF LIGHT

In some cases waves do not always cast sharp shadows, such as in Young's double slit experiment the light rays bend out of their straight line path and spreads into the region beyond the slits which would otherwise be shadow. This effect is common for all types of waves, such as sound waves are spread behind the obstacle or corner, which hides the source. Because the sound waves are bending around the obstacle or corner, water waves on a smooth pond or in a ripple tank do not cast clear shadow of an object as the waves are diffracted. These examples are so common that we do not question their origin.

Besides interference light also exhibits diffraction which provides experimental proof in favour of wave theory of light.

The spreading of light waves round the edges of a narrow opening or the spreading of light in to the region behind an obstacle is called diffraction. The diffraction effects of light can only be observed, when the size of the opening or obstacle is so small that it is comparable with wavelength of light used.

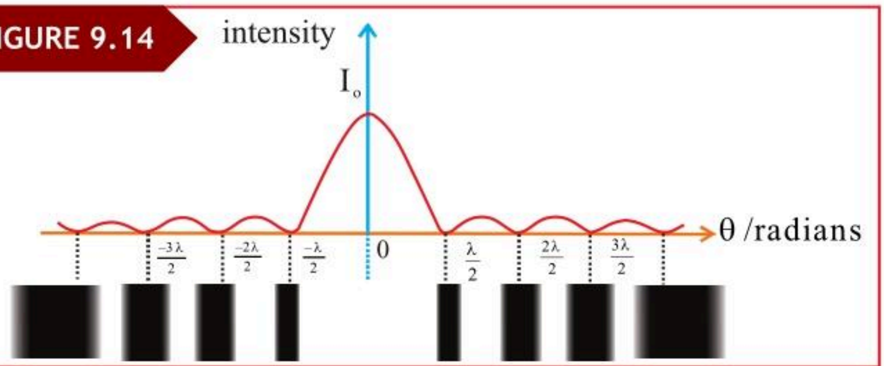
FIGURE 9.13



Narrow gap waves spread out beyond the gap. This spreading is called diffraction.

Diffraction is most obvious when the gap is approximately the same size as the wavelength of the wave.

FIGURE 9.14



In young's double slit experiment the light from the slit *C* simultaneously illuminates the slits *A* and *B*. This is only possible if the light passing through the narrow slit *C*, bends around the corners of *C* and hence spreads out in the region between *C* and the slits *A* & *B*.

(a) The diffraction effects are produced when a beam of monochromatic light passes through a narrow slit as in the Figure 9.13.

It should be noted that the central maximum is of a high intensity and very broad as compared to the other maximum.

(b) Similarly the diffraction effects are exhibited when a knife edge is held up against a monochromatic light source. The diffraction of light waves round the knife edge produces the pattern as shown in Figure 9.14.

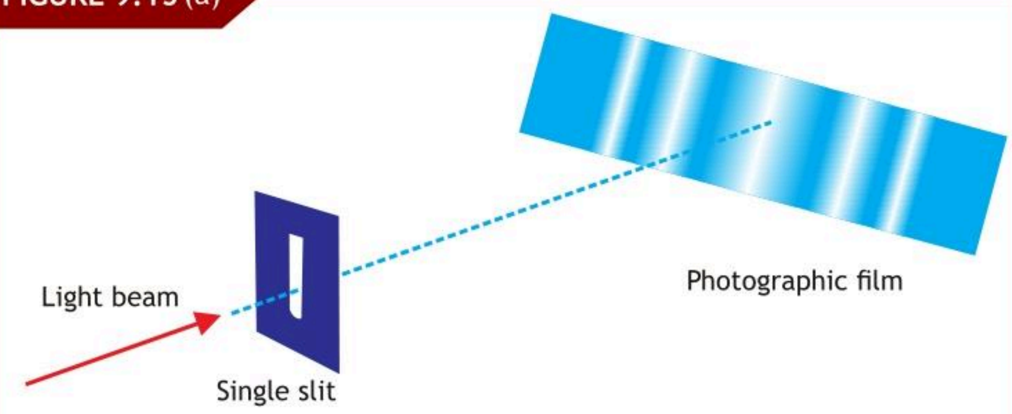
To further describe the diffraction of light, we discuss two different types of experiments.

9.10 DIFFRACTION AT A SINGLE SLIT

The diffraction of light produced by a narrow slit when plane light waves are incident normally on the slit and light waves emerging from the slit are also plane, is called Fraunhofer diffraction.

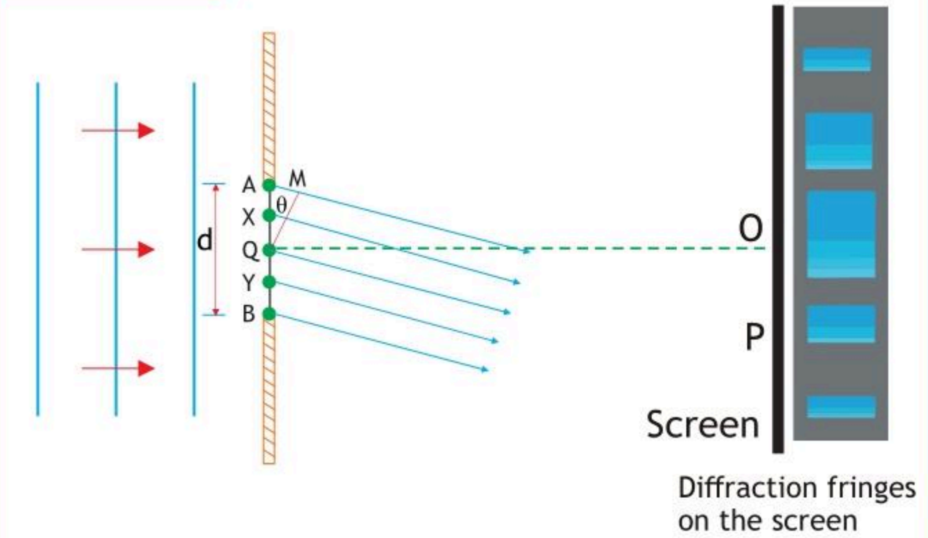
To see the effect of diffraction of light waves we send light through a single slit and record the transmitted light on a photographic film as shown in Figure 9.15(a). Here the central bright is considerably wider than the slit. Moreover, some other bright bands occur on each side of the central image and these must result from some sort of interference effect.

FIGURE 9.15 (a)



Now to see what is involved in this situation, we have to discuss Fraunhofer diffraction, through a single slit. Consider plane wave fronts which are incident on a narrow slit *AB*, as shown in Figure 9.15(b).

FIGURE 9.15 (b)



According to Huygen's principle each point on the wave front at the slit AB acts (as source for the secondary wavelet). At the point O on the screen, which is on the perpendicular bisector of the slit, wavelets from A & B arrive in phase, as theses points are equidistance from O. So there is no path difference between the waves coming from the points A and B as well as from X and Y. Hence constructive interference will occur at O and bright fringe is observed.

It should be noted that for every point on the wave front in AQ, there is a symmetrically located point on the wave front QB. The wavelets sent out by such points to the point O on the screen are in phase. These wavelets superpose and produce a bright spot at O.

Below the point O on the screen, there a point P is selected. The path difference between the wavelets from A and B at the point P is equal to wavelength λ.

The path difference between the wavelets sent out by A and Q to the point P on the screen is approximately equal to half wavelength. Similarly the path difference for the pair of point X & Y and Q & B is also $\lambda/2$.

Hence the wavelets reaching the point P will interfere destructively and dark fringe will be observed. If θ is the angle between QP with the axis of the slit as shown in the Figure 9.15(b) then the angle AQM is also θ, so the equation for the first dark fringe, considering the triangle AMQ is

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

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

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

Similarly it can be shown that for $m\,\lambda$ order minima, we have

$$\sin\theta_m = \frac{m\,\lambda}{d} \qquad (9.10)$$

Where m = 1, 2, 3, ...

The dark fringes are also formed on the other side of the axis QO. In between the dark fringes there are bright fringes. The central maximum (bright fringe) is of highest intensity and all the other maxima are of much lower intensities.

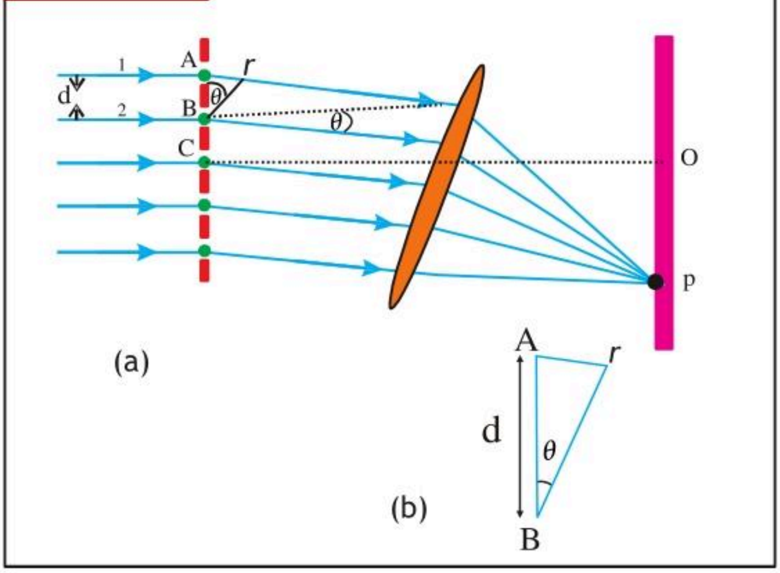
Notice that if a narrow slit is used then the angle θ increases as $\theta = \frac{\lambda}{d}$ when θ is small. This means that a broader central maximum is obtained but the intensity of all the bright fringes decreases as less light passes through the slit.

9.11 DIFFRACTION GRATING

In order to measure the wavelength of light accurately with a practical instrument, a diffraction grating is often used. A device constructed for this purpose is called a grating spectrometer. A grating is basically a glass or plastic plate 2 to 3 cm in length and 2 to 3 mm in thickness, on which a large number of parallel, equally spaced slits of the same width are ruled.

A grating can be made by scratching parallel lines on a glass or plastic plate with special techniques. The spaces between each scratch are transparent to light and hence acts as a separate slit.

FIGURE 9.16



The principle of diffraction grating is based on the interference and diffraction of light waves. The principles of diffraction and interference find important application in the measurement of wavelength with the optical diffraction grating. The light waves after diffraction through the grating are allowed to interfere. The schematic diagram of a common diffraction grating and its working is shown in the Figure 9.16 (a)

A parallel beam of monochromatic light falling on the grating sends out waves from each slit. Along certain directions, waves from the adjacent slits are in phase and reinforce each other. The parallel rays after diffraction through the grating make an angle θ with the normal at the point of incidence. These rays are then brought to focus on the screen at the point P by an achromatic lens. If the path difference between the ray number 1 and number 2 is one wavelength, then they will reinforce each other at P. Similarly waves from any two consecutive slits will differ in path by λ when they arrive at P. They will therefore interfere constructively and bright fringe will be observed at the point P.

Hence the condition for constructive interference is that the path difference Ar between the two consecutive rays should be equal to λ.

$$Ar = \lambda \qquad \text{(i)}$$

But from Figure 9.16 (b) we know that

$$Ar = d\sin\theta \qquad \text{(ii)}$$

r

r

So the above equation becomes $$d \sin\theta = \lambda \tag{3}$$

Where d is the separation between the two slits and is called grating element. Its value is obtained by dividing the unit length of the grating by the total number of lines ruled on it.

$$d = \frac{\text{Unit length of grating}}{\text{Total Number of lines ruled on it}}$$

$$d = \frac{1\text{ cm}}{N}$$

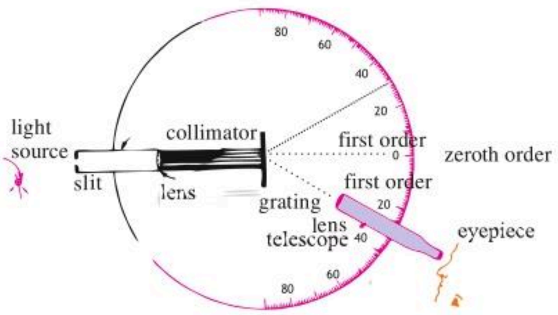
In general there will be other direction on each side of line $\overline{OC}$ for which the waves from adjacent slits differ in path by 2λ, 3λ *etc* and for which the corresponding bright images will be observed. These are called the second, third order images etc. The grating equation can thus be written in more general form as

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

Where m = 0,1,2,3 ……. and is called the order of the image.

For Your Information

Grating spectrometer is used to calculate the wavelength "λ". Consider the diagram in which monochromatic light falls on the grating normally through the collimator. The diffracted light leaves the grating at angle "θ" and telescope is used to view the image as shown. In this way angles for various orders on each side of the central maximum can be measured to calculate the wavelength "λ".



Example 9.4 **DIFFRACTED IMAGE**

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

GIVEN

Number of lines per centimeter = 5000 lines

Angle $\theta = 32^{\circ}$ order of image = $m = 2$

grating element $= d = \dfrac{1\text{cm}}{5000} = 0.00020\text{ cm}$

REQUIRED

wavelength = λ = ?

SOLUTION

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

$$\text{Formula } \lambda = \frac{0.00020\text{ cm} \times \sin 32}{2}$$

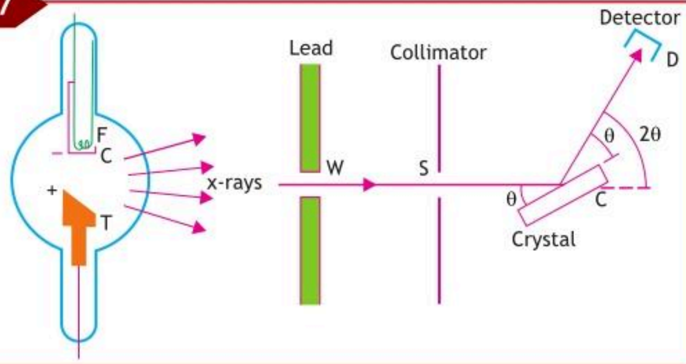
$$\lambda = \frac{0.00020\text{ cm} \times 0.53}{2} = \boxed{5.3\times10^{-5}\text{ cm}}$$

Answer

9.12 THE DIFFRACTION OF X - RAYS BY CRYSTAL

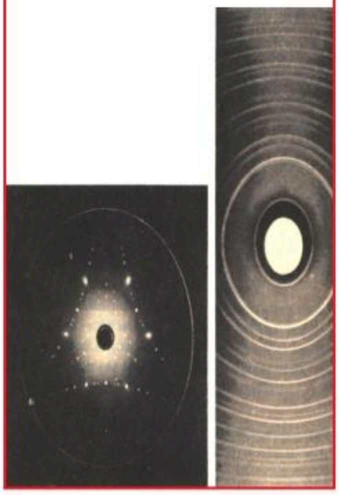
One of the most important application of interference and diffraction is in the study of the structure of crystals. Because in crystals the layers of atoms are less than 1 nm apart, and it is necessary to use very short wavelength radiation to study them. Since X-rays are electromagnetic waves of very short wavelength of the order of 10^{-10} m. It is not possible to produce interference fringes of X-rays by Young's double slit experiment or by thin film method.

FIGURE 9.17



The reason is that the fringes space is given by $L\frac{\lambda}{d}$ and unless the slits are separated by a distance of the order of 10^{-10} m, the fringes obtained will be so closed together that they cannot be observed,. However, it is possible to obtain X-rays diffraction by using sodium chloride (NaCl) crystal which is common table salt. The atoms of crystals are uniformly spaced in planes and are distance *'d'* apart.

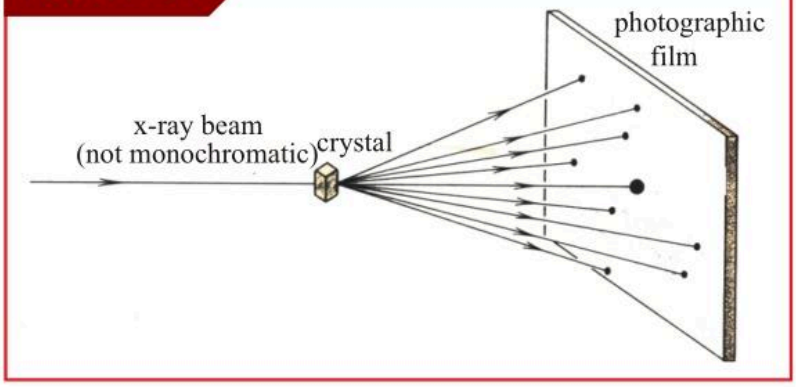
FIGURE 9.18



Experiment

A typical laue type experiment arrangement is shown in the Figure 9.19. A narrow beam of X-rays from the X-ray is collimated through the slit and is allowed to fall on a crystal such as NaCl crystal. The transmitted beam enters the detector D. The laue photograph obtained consists of the central spot surrounded by many other spots arranged in defined pattern. These spots are known as laue spots. The arrangement of laue spots for different crystal is different depending on their structure. These types of experiment prove that X-rays are electromagnetic waves and the atoms are arranged in three dimensional lattices.

FIGURE 9.19



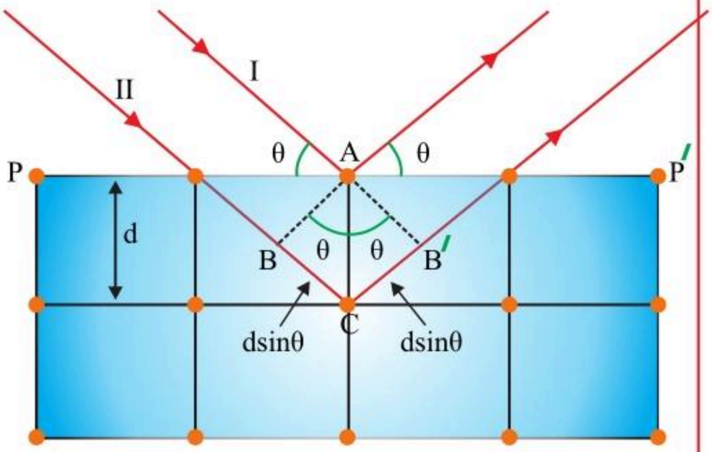
9.12.1 Bragg's Law

To find the wavelength of x-rays beam by crystal we use Bragg's law.

To get an expression for Bragg's law consider the diagram (9.20) in which two parallel rays I and II are incident at the first and second layer of the crystal.

The separation between the two layers is d and θ is the glancing angle which is complementary angle to the angle of incidence.

FIGURE 9.20



braggs law illustration

Now the two reflected rays from the successive planes will reinforce each other if the path difference between them is an integral multiple of wavelength λ.

Since ray II covers larger distance than the ray I so the path difference between the two rays is therefore

$$BC + CB' = m\lambda \qquad (i)$$

But from the diagram we have

$$BC = CB' = d \sin\theta$$

Therefore $2d\sin\theta = m\lambda$ (9.11)

Where m = 1,2,3 ....

This equation is known as Bragg's law. Using Bragg's law we can determine the interplanar spacing between the smaller parallel planes of a crystal, when X-rays of known wavelength are allowed to diffract from the crystal.

The X- ray diffraction has been very useful in determining the structure of biological important molecules such as hemoglobin which is an important constituent of blood and double helix structure of DNA(Deoxyribo Nucleic Acid)

Example 9.5 **X-RAYS OF WAVELENGTH**

X-rays of wavelength 3nm are incident on a crystal for which the lattice spacing is 5nm. Calculate the angle at which the first Bragg diffraction is observed.

GIVEN

Wavelength = λ = 3×10^{-9} m

Lattice spacing = d = 5×10^{-9} m

Order of the image = $m = 1$

REQUIRED

Angle = θ = ?

SOLUTION

Since

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

$$\sin\theta = \frac{m\lambda}{2d} = \frac{1 \times 3 \times 10^{-9}\text{m}}{2 \times 5 \times 10^{-9}\text{m}} = 0.3$$

$$\theta = 17^{o}$$

0.3 **Answer**

ASSIGNMENT:

A beam of X-rays of wavelength 0.3 nm is incident on a crystal, and gives a first-order maximum when the glancing angle is 9.0 degrees. Find the atomic spacing.

9.13 POLARIZATION OF LIGHT

Interference and diffraction effects are the best evidences to prove the wave nature of light. These phenomenon's however, do not tell us whether the light waves are longitudinal or transverse. Polarization of light suggests that the light waves are transverse in character.

Polarization is the process by which the electric and magnetic vibrations of light waves are restricted to a single plane of vibration.

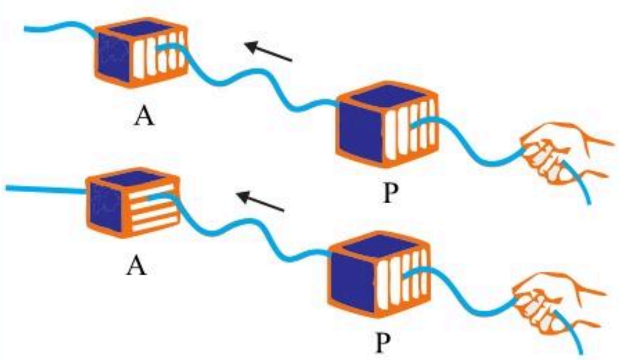
Polarization is the property exhibited by transverse waves only. It does not occur for longitudinal waves such as sound waves .

Experiment with transverse waves:

To study that only transverse wave exhibits polarization property, consider a transverse wave on a string which passes through a slot *"P"* in a wooden board as shown in the Figure 9.21.

When the slot is parallel to the direction of the transverse vibrations the wave passes through the slot un-disturbed. But if another slot is held at right angle to the first one then no wave will pass through the second one.

FIGURE 9.21



polarization of transverse waves

If the string is replaced by a spring and longitudinal (compressional) wave is set into it, the wave will pass through the slots regardless of the orientation of the slots. This shows that longitudinal waves do not show polarization property.

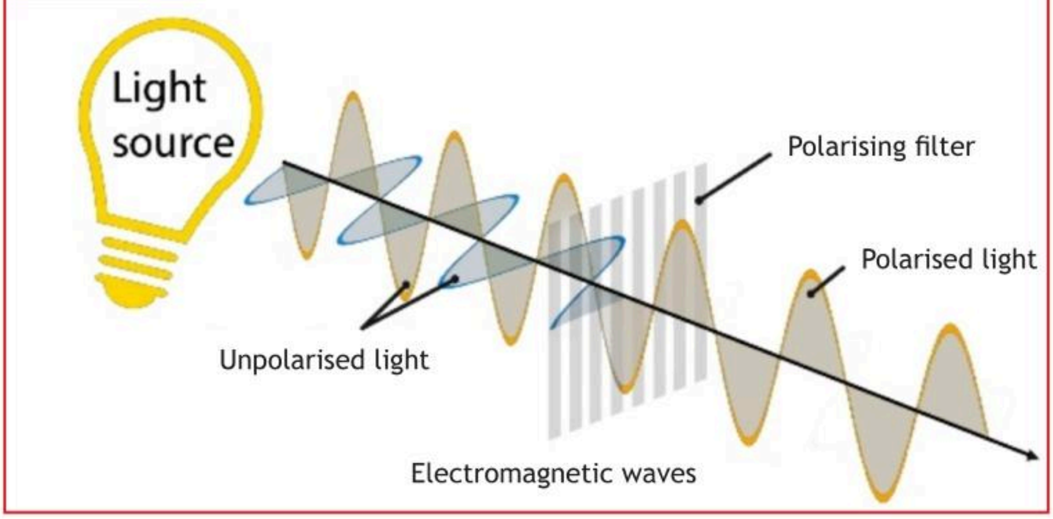
DO YOU KNOW?

It is very effective to use a polarized sun glasses than using ordinary sun glasses.

9.13.1 Ordinary Light

Question arises that why ordinary light is not polarized? To answer this question, we know that light wave is emitted when an electron orbiting around a nucleus jumps from higher energy level to a lower energy state. If the transition is due to an electron orbiting in a vertical plane, the light wave emitting is polarized in the vertical plane. But if the transition is due to an electron orbiting in a horizontal orbit then the light wave emitted is polarized in the horizontal plane. The light waves emitted from a source such as candle flame, a filament of bulb or the sun is non polarized. This is because the light waves are from different atoms whose electrons experiencing the transition in different planes in all direction.

FIGURE 9.22



Therefore light waves are electromagnetic waves which consist of periodic vibrations of electric field vectors *"E"* accompanied by the magnetic field vector *"B"* at right angled to each other as shown in Figure . 9.22.

9.13.2 Production of Polarized Light

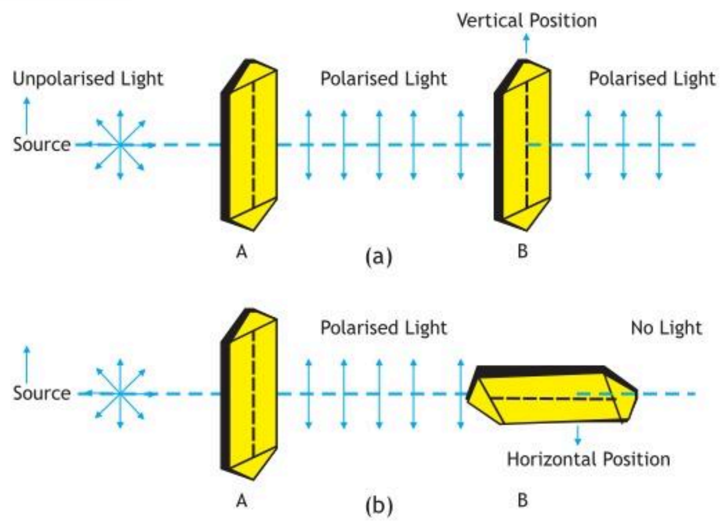
It is possible to obtain plane polarized beam of light from un-polarized light by removing all the waves from the beam except those having vibrations along one particular direction. This can be achieved by various processes given below.

i. Selective absorption
ii. Reflection from surface
iii. Refraction through crystals
iv. Scattering by tiny particles

The selective absorption method is the most common method to obtain plane polarized light by using certain Polaroid crystal called dichroic substance. It is made up from tiny crystals of quinine iodosulphate. Such a crystal has property to transmit all the vibrations parallel to its crystallographic axis while absorbs all the remaining vibrations.

To get the polarization of light, we perform an experiment with two tourmaline crystals as shown in the Figure 9.23. The ordinary un-polarized light falls on a tourmaline crystal from the source. The internal molecular structure of the crystal is such that it allows only those electric and magnetic vibrations which are parallel to its crystallographic axis and absorbs all the remaining vibrations.

FIGURE 9.23



polarization of light

Thus the light passed through this crystal has all the fields' of vibrations in one plane and is known as the plane polarized light. When another tourmaline crystal is placed in the path of this polarized light in such a way that its crystallographic axis is parallel to the first one, then the polarized light will completely transmit through it. If it is rotated around the ray of light so that axis of the two crystals are inclined, the intensity of the transmitted light decreases, when the axis become at right angle to each other, then no light will pass through the second crystal. When the second crystal is further rotated, the emergent light will again appear. Therefore the second crystal is known as analyzer. In this way we can obtain a beam of polarized light.

9.13.3 Polarization by Reflection

When un-polarized light falls on glass, water etc, the reflected light is in general partially plane polarized but at a certain angle of incidence called polarizing angle, the polarization is complete. At this angle the reflected ray and the refracted ray in a transmitted medium are found to be at right angle to each other.

The vibrations in the reflected ray are parallel to the surface, as shown, Applying Snell's law we have

$$n_1 \sin i_p = n_2 \sin r \qquad (9.12)$$

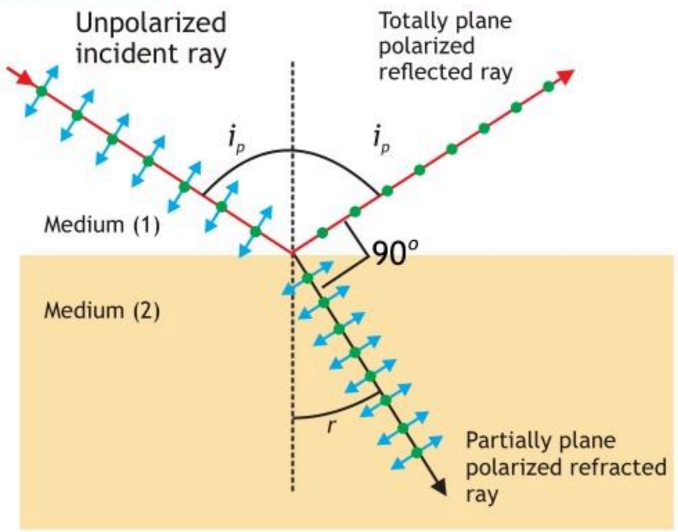
Where n_1 and n_2 are the absolute refractive indexes of the medium 1 and 2. Since from the Figure 9.24 we have

$$i_p + 90^o + r = 180^o$$

$$r = 90^o - i_p$$

Hence, putting this value in Eq (9.12)

FIGURE 9.24



polarization of light after reflection

$$n_1 \sin i_p = n_2 \sin (90 - i_p) \qquad \text{(i)}$$

$$n_1 \sin i_p = n_2 \cos i_p \qquad \text{(ii)}$$

$$\frac{n_2}{n_1} = \frac{\sin i_p}{\cos i_p}$$

$$\frac{n_2}{n_1} = \tan i_p \qquad (9.13)$$

This is known as Brewster's law. For glass of refractive index 1.55, the angle of incidence $i_p = 57^o$

ACTIVITY

Take a pair of inexpensive polarized sunglasses outside on a sunny day and analyze the polarization of the sky in various directions (but do not look directly at the Sun, even through sunglasses!). Get a second pair of sunglasses so you can put two polarizers in series. Rotate the one closest to you while holding the other in the same orientation. When is the transmitted intensity maximum? When is it minimum?

9.13.4 Applications of Polarized Light

i. Reducing glare

Glare caused by light reflected from a smooth surface such as roads and lakes can be reduced by using polarizing materials as the reflected light is partially or completely polarized. Thus Polaroid discs, suitably oriented are used in sun glasses to avoid the polarized light.

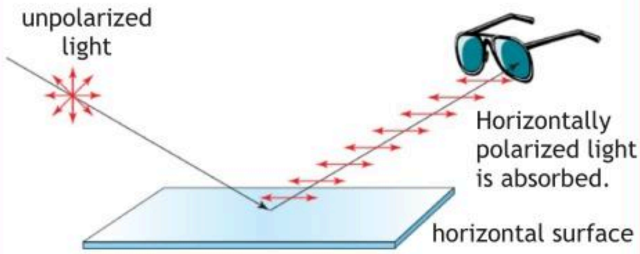
Similarly in photography, the Polaroid discs are placed in front of the camera lens which enabling us to see the detail which would be other wise hidden by glare.

ii. Optical Activity

When a beam of light is made to pass through certain crystals (Quartz), or liquids, (Sugar solution), the directions of vibration of the transmitted polarized light is found to be rotated. This phenomenon is called optical activity. For a solution the angle of rotation depends on its concentration, and an instrument known as a polarimeter is used to measure the concentration of the given solution. In sugar mills, polarimeter is used to measure the sugar concentration in the solution obtained from sugar cane.

Do You Know?

When light is reflecting from the glass then it is partially polarized.



Since glare is caused by reflected light that is horizontally polarized, sunglasses with polarized lenses can eliminate glare by allowing only vertically polarized light to pass through.

iii. Curtianless window

Two polarizing sheets are fixed in a window, one inside and the other outside. The inner one is rotated in such a way to adjust the amount of light to be admitted.

iv. Control of head light glare

During night safe driving is possible if each car having polarizing head lights and polarized light viewer. Polaroid glasses eliminate the glare of light as it is partly polarized by reflection from water and road.

v. Stress analysis

When glass, Polythene and some other plastics are under stress (e.g.,) by bending, twisting or uneven heating) they become doubly refracting and if viewed in white light between two 'crossed' Polaroid's colourd fringes are seen round the regions of strain'. This effect is called photo elasticity and is used to analyze stresses in plastic model of various structures.

KEY POINTS

Nature of light: According to modern concept the nature of light is dual. Some time it behaves as a wave such as in reflection, refraction, particle, such as photo-electric effect and Compton Effect.

Wave front: diffraction, interference and polarization. But some time it behaves as the locus of all the points in a medium which have the same phase, is called a wavefront.

Ray: The arrows to indicate the direction of wave fronts are known as the rays. The rays are always perpendicular to the wave fronts.

Phase coherent sources: The two sources of light which maintains a constant phase relationship between their waves during emission are called phase coherent sources.

Interference of light waves: The effect produced to the superposition of two coherent waves is known as interference.

Diffraction: The bending of light waves around an obstacle and spreading into its geometrical shadow is called diffraction.

Polarization of light: The process by which the electric and magnetic vibrations of light waves are restricted to a single plane of vibration is called polarization of light.

EXERCISE

MULTIPLE CHOICE QUESTIONS

Choose the best possible answer

1. The principle of Young's double slits experiment is based on the division of:
   a. Amplitude b. Frequency c. Velocity d. Wavelength

2. Which one of the following properties proves the transverse wave nature of light.
   a. Interference b. Refraction c. Polarization d. Diffraction

3. Coloured fringes observed in soap bubbles are the examples of
   a. Diffraction b. Interference c. Polarization d. Reflection

4. During a sunny day we see the objects in a class room even when all the electric lights are off, due to
   a. Reflection of light b. Refraction of light
   c. Diffraction of light d. Interference of light

5. The principle of Michelson interferometer is based on the division of
   a. Wavefront b. Amplitude c. Frequency d. Speed of light

6. In the Young's double slit experiment the separation between the slits is halved and the distance between the slits and the screen is doubled. The fringe width is
   a. Halved b. Unchanged c. Doubled d. Quadrupled

7. Signal from a remote control to the device operated by it travels with the speed of:
   a. Sound b. Light c. Ultrasonic d. Supersonics

8. Light of wavelength λ is incident normally on a diffraction grating for which the slit spacing is equal to 3λ. What is the sine of the angle between the second order maximum and the normal?
   a. $\frac{1}{6}$ b. $\frac{1}{3}$ c. $\frac{2}{3}$ d. 1

9. Which of the following gives three regions of the electromagnetic spectrum in order of increasing wavelength, visible radiation
   a. Gamma rays, microwaves, visible radiation
   b. Radio waves, ultraviolet, X-rays
   c. Ultraviolet, infra-red microwaves
   d. Visible radiation, gamma rays, radio waves
10. Two monochromatic radiations X and Y are incident normally on a diffraction grating. The second order intensity maximum for X coincides with the third order intensity maximum for Y. What is the ratio $\frac{\text{wavelength of X}}{\text{wavelength of Y}}$?
   a. $\frac{1}{2}$ b. $\frac{2}{3}$ c. $\frac{3}{2}$ d. $\frac{2}{1}$
11. The tip of a needle does not give a sharp image. It is due to
   a. Polarization b. Interference c. Diffraction d. Refraction

CONCEPTUAL QUESTIONS

Give a short response to the following questions

1. A soap bubble looks black when it bursts, why?
2. What is the difference between interference and diffraction?
3. In a Michelson interferometer a second glass plate is also used, why?
4. How you can explain Brewster's law of polarization?
5. What is meant by the path difference with reference to the interference of two wave motion?
6. Why it is not possible to see the interference where the light beams from the head lamps of a car overlap?
7. A telephone pole casts a clear shadow in the light from a distant head lamp of a car, but no such effect is noticed for the sound from the car horn. Why?
8. Why it is not possible to obtained the diffraction of X-rays by Young's double slits experiment?

9. Can we apply Huygen's principle to radar waves?
10. How would you justify that light waves are transverse?

COMPREHENSIVE QUESTIONS

Give extended response to the following question

1. What is meant by the dual nature of light? Discuss the history about the nature of light in detail.
2. Explain the diffraction of X-rays by crystal and derive an expression for Bragg's law to find the wavelength of light used?
3. Describe the experimental arrangement for the production of interference
   fringes by Young's double slits method, and get an expression for the fringes space.
4. State and explain Huygen's principle. What is the difference between spherical and plane wavefronts?
5. Explain the interference effect produced by thin film.
6. What is the principle of interference of light? Discuss the necessary condition for interference of light
7. What is diffraction grating? How can the wavelength of a beam of light be measured with it?
8. Describe the construction and working of Michelson's interferometer. How one can determine the wavelength of light used by this instrument?
9. What is meant by plane polarized light? How does this phenomenon decide that light waves are transverse in nature?

NUMERICAL QUESTIONS

1. In a young double slit experiment the separation of the slits is 1 mm and red light of wavelength 620 nm is falling on it. Determine the distance between the central bright band and the fifth bright fringe on the screen which is 3m away from the slit. (9.3 mm)

2. Two parallel slits are illuminated by light of two wavelengths, one of which is 5.8×10^{-7} m. On the screen the fourth dark line of the known wavelength coincides with the fifth bright line of the light of unknown wavelength. Find the unknown wavelength. (5.2×10^{-7}m)

3. When the movable mirror of a Michelson interferometer is moved 0.1 mm. How may dark fringes pass through the reference point, if light of wavelength 580 nm is used? (345 fringes)

4. A soap film has a refractive index of 1.40. How thick must the film be, if it appears black, when mercury light of wavelength 546.1 nm falls on it normally? (1.95×10^{-7} m)

5. A diffraction grating has 5000 lines per centimeter. At what angle does the second order spectrum of the sodium yellow light of wavelength 589 nm occur? (0.36°)

6. Light is incident normally on a grating which has 250 lines / mm. Find the wavelength of spectral line for which the deviation in second order is 12°. ($\lambda = 4158 \times 10^{-10}$m)

7. In a certain X-rays diffraction experiment the first order image is observed at an angle of 5° for a crystal plane spacing of 2.8×10^{-10} m. What is the wavelength of X-rays used? ($\lambda = 0.49 \times 10^{-10}$m)

8. An X-ray beam of wavelength 0.48×10^{-10}m is used to get Bragg reflection from a crystal at an angle of 20° for the first order maximum. What are the possible layer plane spacing which give rise to this maximum? (0.70×10^{-10}m)

9. The spacing of one set of crystal planes in NaCl (table salt) is d = 0.282 nm. A monochromatic beam of X-rays produces a Bragg maximum when its glancing angle with these planes is $\theta = 7^{\circ}$. Assuming that this is a first order maximum (n = 1), find the wavelength of the X-rays. (0.069 nm)