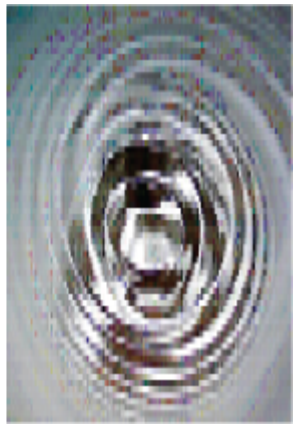


2

WAVE PROPERTIES AND ELECTROMAGNETIC WAVES

Properties of waves

In Book 2, we studied reflection and refraction as two properties of waves. We will now consider the remaining properties of waves like **diffraction, interference** and **polarization. Polarization** is the property of transverse waves alone. Longitudinal waves have no vertical vibration and cannot be polarized.

OBJECTIVES

At the end of this topic, students should be able to:

→state and explain four properties of waves;
→demonstrate interference of waves;
→demonstrate polarization of light waves;
→demonstrate diffraction of waves.

Diffraction of waves

Diffraction is the spreading of waves round an obstacle or through a narrow opening.

When plane wave fronts pass through a narrow opening, they spread in all direction on the other side of the opening. Diffraction occurs if the size of the opening is less than the wavelength of the incident wave. The smaller the opening, the clearer the diffraction and the wider the opening compared with the wavelength of the incident wave, the less pronounced is the diffraction. Diffraction of water waves is shown in Figure 2.1.

Sound waves are diffracted like water waves. Diffraction of sound is mostly noticed because the wavelength of sound is greater than most opening around us. When we speak inside a room, the sound waves are diffracted through the doors, windows and other openings to the outside. This is why we could hear a sound even when the source is out of sight. Light is the visible part of an electromagnetic wave and therefore can be diffracted.

The wavelength of light is very short and hardly diffracts through large openings. This is the reason why it is not easy to observe diffraction of light. To observe the diffraction of light waves, we must use openings close to the wavelength of light. This is achieved using crystals with atomic spacing in the order of the wavelength of light.

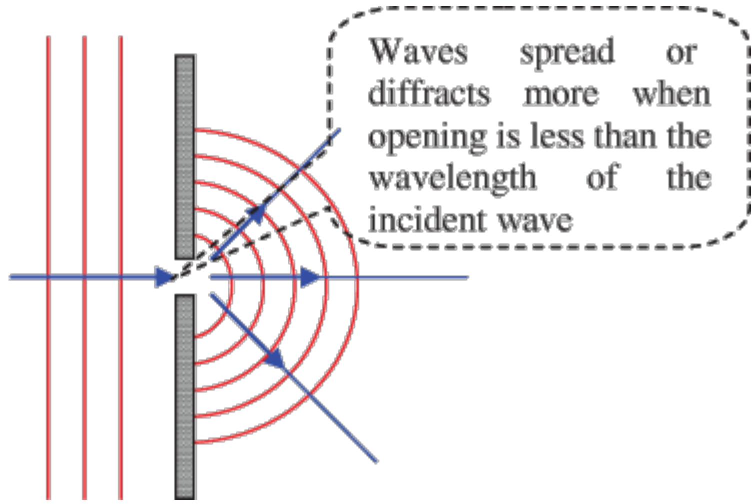


Figure 2.1: Diffraction through a narow openning

Interference of waves

When two waves meet, they interfere to form a new wave. The addition of two waves is called **superimposition** or **interference** while the disturbance produced is called **interference pattern.**

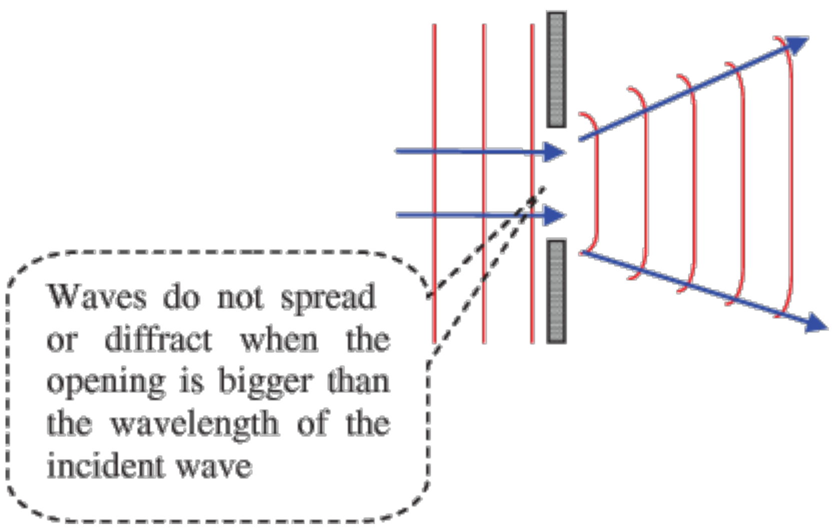


Figure 2.2: Diffraction through a wide openning

Principle of superimposition

The principle of superimposition states that if two waves travelling in the same medium meet, a new wave is formed, with an amplitude equal to the algebraic sum of the amplitudes of the two interfering waves.

Interference is the meeting or addition of two waves to produce a new wave of larger or smaller amplitude.

The interference pattern formed depends on how the waves arrive at a given spot or the directions of the interfering waves.

Constructive interference

If the two interfering waves arrive at a spot in phase (that is, the crest of one wave overlaps the crest of the other wave or the trough overlaps the trough of the other wave), the waves add up to form a bigger wave. The reinforced or bigger wave is called **constructive interference.**

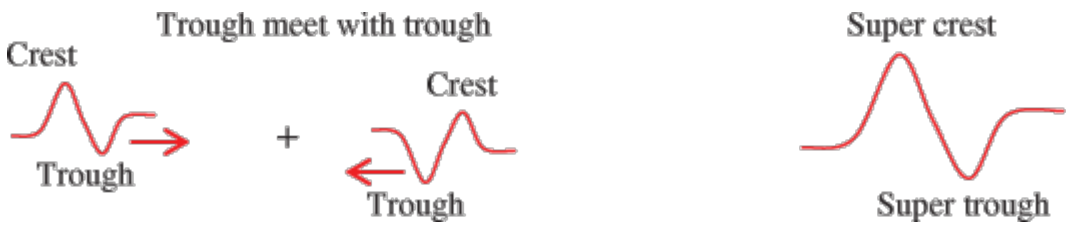


Figure 2.3a: Constructive interference

Destructive interference

At another spot, the two waves arrive exactly out of phase such that the crest of one wave overlaps the trough of another wave to form no wave or a wave of zero amplitude. The cancellation of the waves is called **destructive interference**.

Figure 2.3b: Destructive interference

Interference is produced when two similar waves moving in the opposite direction overlap. Usually, an **incident wave** and its **reflection** overlap to form another wave with varying amplitudes. The new wave produced is called **standing** or **stationary wave.**

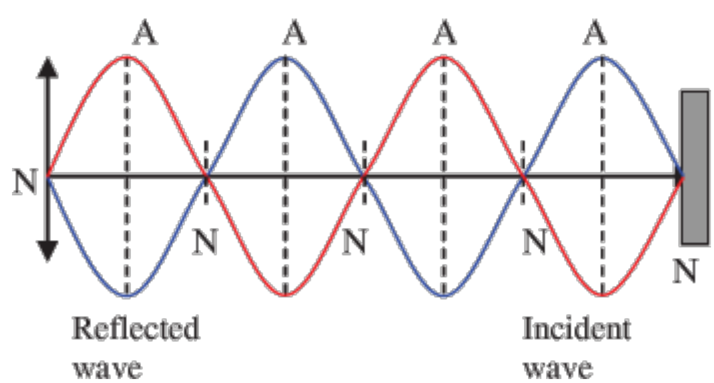


Figure 2.4: Stationary wave

Along the stationary wave there are *points of maximum disturbance or reinforcement* *called* ***antinodes*** (A). The particles are vibrating with maximum amplitude at the antinodes and the interference is constructive. The points formed along the stationary wave where the particles of the medium are at rest are called **nodes** (N). *Nodes are the points of cancellation or destructive interference of the waves.*

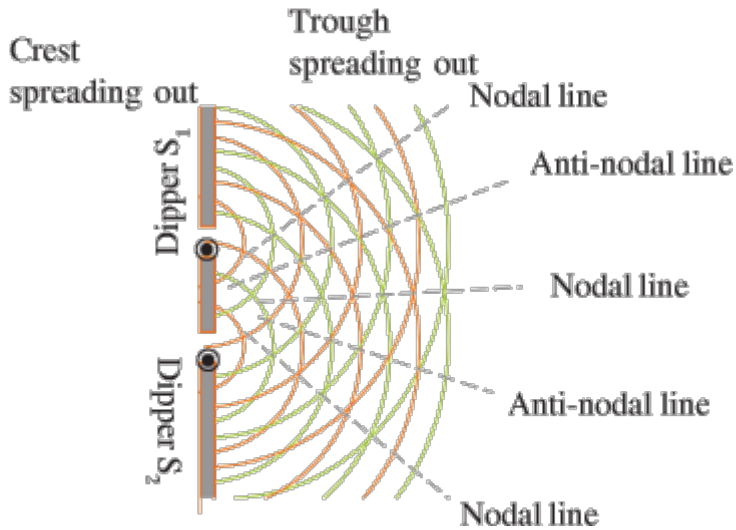


Figure 2.5 Interference of waves

Interference of water waves

Interference of water waves can be studied using the ripple tank. The water is disturbed at two points with dippers S_1 and S_2 vibrating at the same frequency and producing waves of equal amplitude. Waves produced by the dippers S_1 and S_2 overlap at regular intervals as they spread. The interference pattern is shown in Figure 2.5.

The circular waves spreading outwards from S_1 and S_2 superimpose one another. *At some places, the crests of the two waves overlap to form regions of* **reinforcement** *or* ***maximum disturbances*** *called* **constructive interference.** The imaginary line joining the regions of reinforcement or maximum disturbances is called the anti-nodal line. *At some places, the crest of one wave overlaps with the trough of another wave to produce* ***no disturbance*** *or* **cancellation of wave** *called* **destructive interference.** The imaginary line joining the regions of destructive interference is called nodal line.

Interference of light waves

Light is a wave and can produce interference pattern similar to water waves. The wavelength of light is very small therefore, the interference of light is observed under some special conditions. These conditions are:

- The source of light must be **coherent.**

  The two interfering light waves must have the same frequency and wavelength. A source of light radiating one frequency is said to be **monochromatic.**

- The two interfering waves must keep a constant phase difference between them.

  The waves must reach a given spot in phase or exactly out of phase. The two waves reach the same spot in phase when they travel the same distance or the difference in the distance they travel is one wavelength or integral multiples of wavelength. (Ï• = 0, Î», 2Î», 3Î» â€¦)

- The two waves must have nearly the same amplitude.

Regions of cancellation of waves are only possible if the two waves have equal amplitude.

The pattern of interference produced by waves is shown in Figure 2.6. It consists of series of dark lines and bright lines called **interference fringes.** This gives a good evidence that light is a wave. The bright lines represent the regions reinforcement or constructive of interference (R); the dark lines represent regions of cancellation of waves or destructive interference (D).

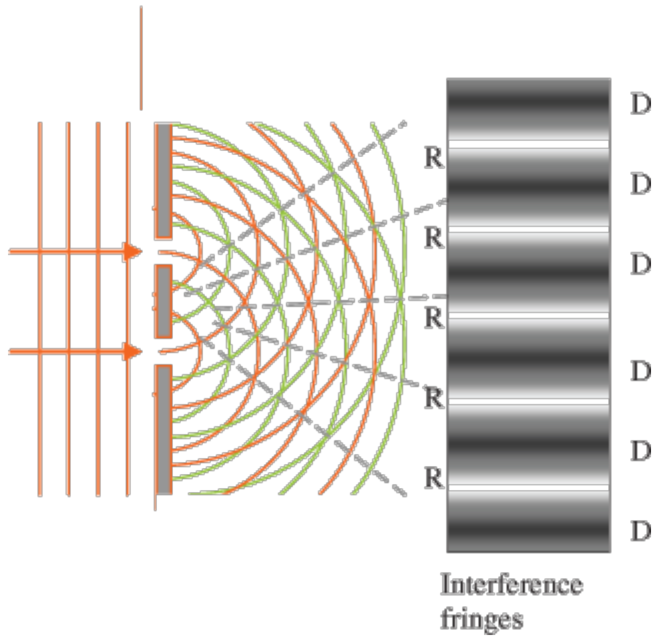


Figure 2.6: Interference of light

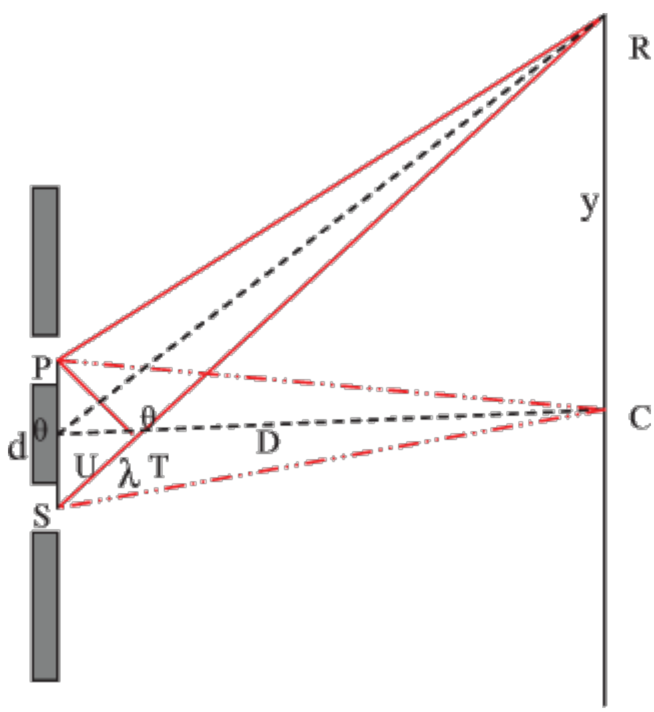


Figure 2.7: Formation of bright and dark

Thomas Young first produced the interference of light waves in 1801. The formation of bright lines and dark lines can be explained using Figure 2.7.

The point C is the central bright line. The light from P and S travels the same distance to arrive at the point C in phase. Their path difference is zero. The next bright line is at R. Light from S travelled a longer distance than light from P to arrive at the point R in phase. The difference in the distance travelled by the two light rays (path difference) is equal to one wavelength (Î»).

â^´ ST = SR – PR

l = SR – PR

Triangle PST is similar to triangle URC. Using the triangles it can be shown that:

$$\frac{ST}{SP} = \frac{RC}{UC}$$

$$\frac{\lambda}{d} = \frac{y}{D}$$

$$\lambda = \frac{y \times d}{D}$$

y = distance between two bright fringes

Î» = wavelength of light

d = distance between the double slits

D = distance between the screen and slits

How to measure the wavelength of light

Apparatus: A monochromatic source of light (a lit candle can serve), double slit (made by drawing two parallel lines (Â» 0.5mm) on coated glass), translucent screen and metre rule.

Method:

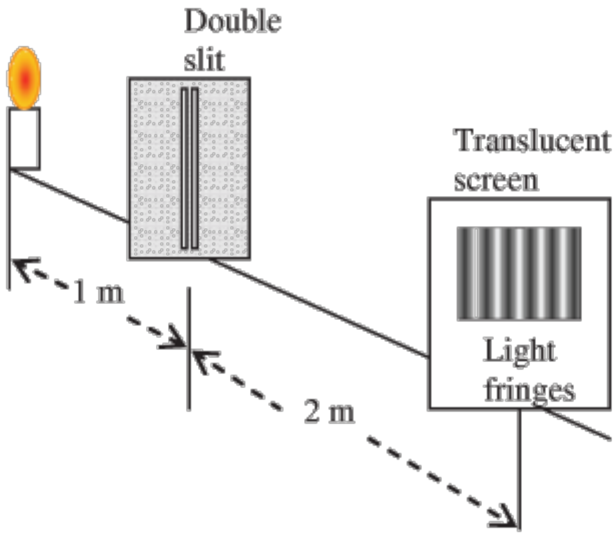


Figure 2.8: Demonstration of light interference

The double slit is placed 1 m from the lit candle and 2 m from a translucent screen in a dark room. A series of bright and dark lines are formed on the screen. If the separation between the two bright fringes is carefully measured, we can calculate the speed of light using the equation.

$$\lambda = \frac{y \times d}{D}$$

Colour and wavelength

The colour of white light depends on its wavelength. **Red light has the longest wavelength** in the visible spectrum. The wavelength decreases from red to violet. The double slit experiment in Figure 2.8 is used to confirm this. When different coloured filters are used to cover the slits, bright and dark fringes are formed on the screen as shown in Figure 2.9. The separation between bright fringes is greatest for red. The blue light has a shorter wavelength than red light.

Bright and dark blue fringes

Bright and dark red fringes

Figure 2.9 : Interference of blue and red light

Polarization of waves

Polarization is a property of transverse waves only. A transverse wave is polarized if it vibrates or oscillates in one plane (direction) only. An unpolarized wave vibrates in many different directions.

Polarization is the restriction of wave in one plane or in one direction only.

A wave is plane-polarized if it is allowed to vibrate in one direction or plane only.

Mechanical analogue of polarization

A mechanical wave is set up in a rope in a vertical direction by moving the rope up and down. The rope passes through a vertical slit placed in its path but cannot pass through a horizontal slit. The horizontal slit stops the rope because its opening is not in the same direction as the vibration of the rope.

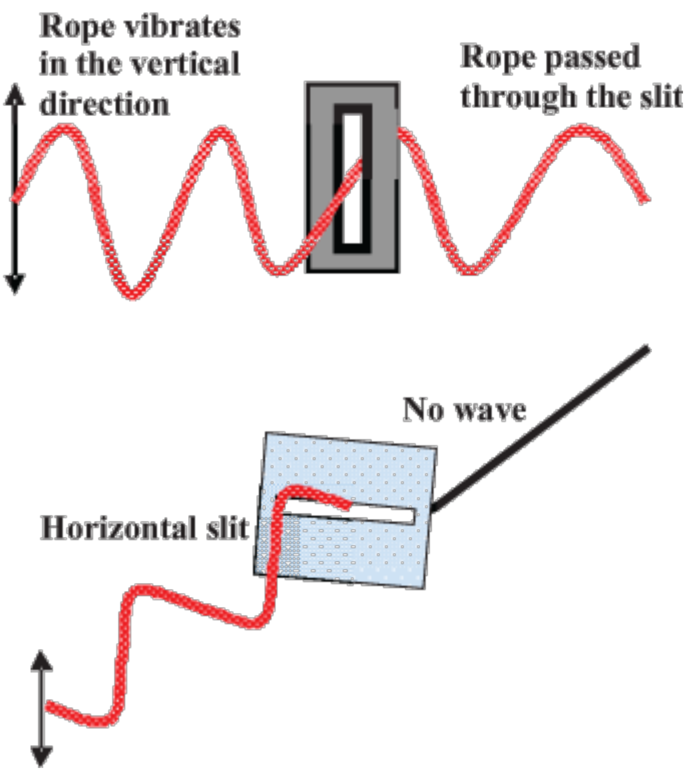


Figure 2.10: Demonstration of polarization

Polarization of light waves

Light waves from lamp bulb are unpolarized transverse waves. Their vibration is sent out in every direction as illustrated in figure 2.11.

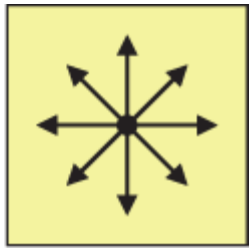


Figure 2.11: Unpolarized light

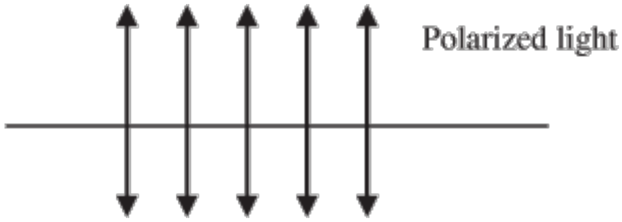


Figure 2.12: Plane polarized light

A polarized light is produced if an unpolarized light passes through a **polaroid.** A polaroid is a special material, which allows light waves vibrating in one direction to pass through. The vibration in a given plane transmitted is determined by the arrangement of the polaroid molecules. The vibration in a plane parallel to the direction of the polaroid molecules (slits) will pass through the polaroid. A polaroid with vertical slits will permit only light waves vibrating in the vertical direction to pass through. A polaroid with vertical slit will block light vibrating in any other direction.

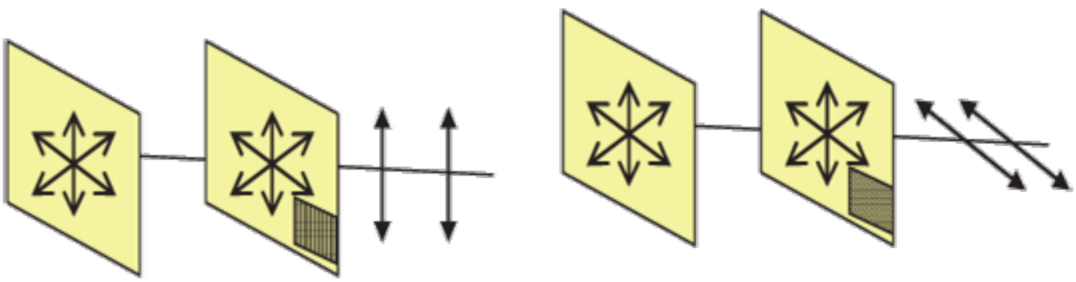


Figure 2.13: Production of polarized light

Ways of producing plane-polarized light

(i) A plane-polarized wave is produced by passing unpolarized light through a polaroid.

(ii) Another way to produce plane polarized light is by reflection from water or other reflecting surface.

(iii) A plane-polarized light is also produced by refraction. An unpolarized light is passed through a crystal which splits it into two plane-polarized light.

(iv) An unpolarized light is scattered by particles or water drops in the air to produce plane polarized light.

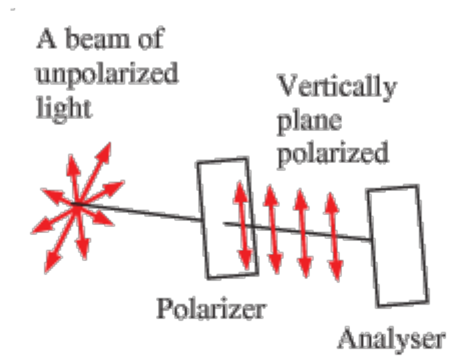
Detection of plane polarized light

Plane polarized light can be detected by placing another polaroid called analyser in the path of a plane polarized light. The analyzer is then turned until the light is cut off. This happens because light polarized in one plane by a polaroid cannot pass through a second polaroid held at right angle to the first polaroid.

Production of polarization of light by reflection

If light is incident on a transparent medium like water or glass at an angle of 57Â° called Brewster or polarizing angle, the component of light vibrating parallel to the plane of incidence is not reflected. The component of light reflected is partially plane polarized. A completely plane polarized light is produced when the reflected and refracted light are perpendicular, that is, the angle between them is 90Â°. The refractive index of the medium is the tangent of the Brewster angle. The Brewster or polarizing angle for glass is about 57Â°.

The angle of refraction (r) and the polarizing angle (Î¸) are related by r + Î¸ = 90. Therefore, r = 90 – Î¸. The refractive index (n) of the medium according to Snellâ€™s law of refraction is given by:



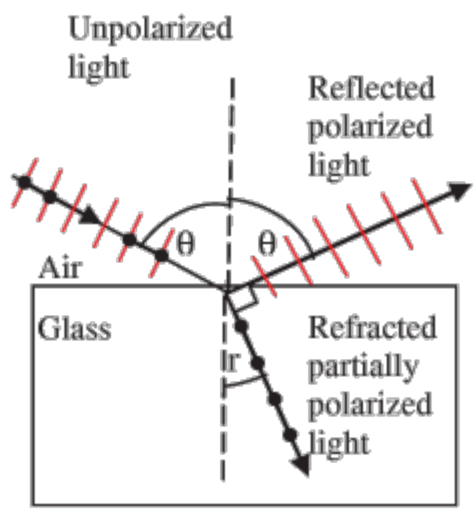
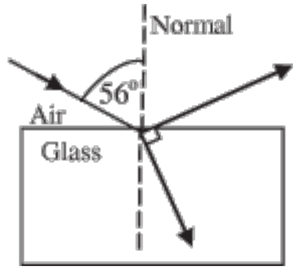


Figure 2.14: Polarized light by reflection

$$n = \frac{\sin i}{\sin r} = \frac{\sin\theta}{\sin(90-\theta)} = \frac{\sin\theta}{\cos\theta} = \tan\theta$$

Example 1

A ray of light is incident on a glass block as shown in the diagram. If the reflected and refracted rays are perpendicular to each other, what is the refractive index of glass relative to air?



Solution

Method 1

Refractive index (n) = tan Î¸ = tan 56Â° = 1.48

Method 2 Refractive index $(n) = \frac{\sin i}{\sin r}$ but $r = 90^\circ - 56^\circ$

r = 34Â°

$$n = \frac{\sin i}{\sin r} = \frac{\sin 56}{\sin 34} = \frac{0.8290}{0.5592} = 1.48$$

Example 2

A beam of light is incident on a transparent material whose refractive index is 1.825. Calculate to the nearest degree, the angle of incidence of the light beam on the material if the reflected and the refracted light beams are perpendicular.

Solution

Refractive index (n) = tan Î¸ = 1.825

â‡’ Î¸ = tan^{-1} 1.825 = 61.28Â° â‰ˆ 61Â°

Uses of polaroid (plane polarized light)

1. Polaroid filters are used in liquid crystals displays (LCDs) in calculators and wrist watches.
2. Sunglasses are polaroid glasses designed to reduce the glare from the reflecting surfaces or intensity of incident sunlight.
3. Polaroid is used to produce polarized light.
4. Polarizing filters are used in cameras to shut out light instead of shades. Two polaroid filters are arranged in such a way that their slits are perpendicular. The first polarized filter or polarizer produces polarized light while the second filter or analyzer cuts off the light.
5. Polarized light is used in holography (the production of 3-dimensional pictures/film).
6. Polarized light is used in stress analysis of glass, perspex, polythene and plastics under stress.
7. Polarized light is used in saccharimetry to find the concentration of sugar in a solution.

Summary

- **Diffraction** is the spreading of waves around the edges of obstacles. It occurs when the opening is smaller or equal to the wavelength of the incident wave.
- **Interference** is the meeting or addition of two waves to produce a new wave of larger or smaller amplitude.
- **Constructive interference** occurs when the two interfering waves meet to produce a reinforced or bigger wave. This happens if the waves arrive at the same spot in phase (crest to crest or trough to trough).
- **Destructive interference** occurs if the two interfering waves overlap to cancel out or form no wave (zero amplitude).
- The interference of incident and reflected waves produce a new wave called **standing** or **stationary wave.**
- The **colour of white light** depends on its wavelength. Red light has the longest wavelength in the visible spectrum.
- **A plane-polarized wave** is one which vibrates in only one direction or plane.

Practice Questions 2a

1 (a) What is diffraction of waves? State the condition necessary for diffraction of waves.

(b) Explain why it is difficult to observe the diffraction of light waves.

(c) Why is diffraction of sound easily observed everywhere?

2 (a) Define interference of waves and state the conditions that must be fulfilled before two interfering lights will produce interference fringes.

(b) Using the interference fringes of red and blue lights, explain why the wavelength of blue light is shorter than the wavelength of red light.

3 With the help of sketches, explain the following;

(i) constructive interference;

(ii) destructive interference.

4 (a) Explain what is meant by coherent source of light as used in the interference of light.

(b) Give an outline of how to find the wavelength of light using double slit in Youngâ€™s experiment.

(c) State three quantities that should be measured and write the formula connecting them.

5 (a) Explain what is meant by plane polarized wave.

(b) State two:

(i) ways to produce plane polarized light;

(ii) uses of plane polarized light.

Electromagnetic Waves

OBJECTIVES:

At the end of this topic, students should be able to:

- →explain dispersion, obtain the spectrum of white light and recall the colours of the spectrum of white light;
- →explain how white light splits into its component colours;
- →state the primary and secondary colours of white light;
- →explain colour mixing by addition and subtraction.

Visible light is just a small part of the radiation called **electromagnetic waves.** Electromagnetic waves are group of waves consisting of radio waves, microwaves, infrared, visible light, ultraviolet, X-rays and gamma rays. These waves are a combination of an **electric field and a magnetic field vibrating at right angle and independent of each other and to the direction the wave is travelling.** This is illustrated in Figure 2.15.

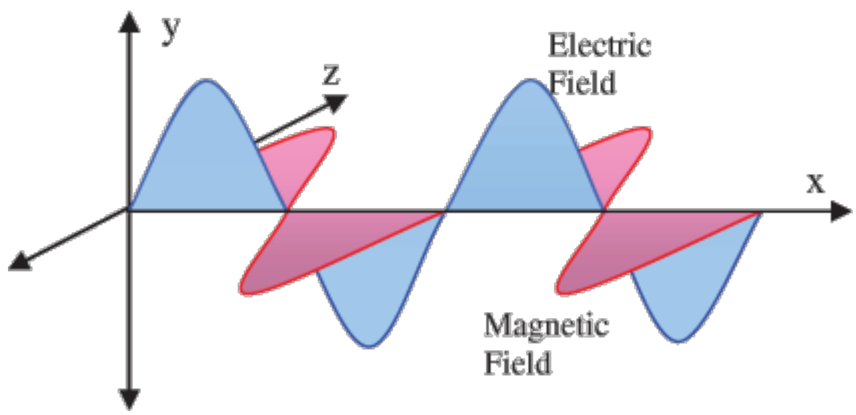


Figure 2.15: Vibration of electric and magnetic waves to form electromagnetic waves

The wavelength of this family of waves known as electromagnetic waves is continuous but vary between thousands of metres (103 m) for radio waves and 10^{-12} m for gamma rays. **The range of wavelengths within this family of waves is called electromagnetic spectrum.**

Each member of this family of waves has the following common properties:

- They are all electric field vibrating at right angle to the magnetic field.
- They travel through air or vacuum with the same speed of light (3.0 Ã— 10^{8} ms^{-1}).
- They are all transverse waves and can be polarized like other transverse waves.
- They are not affected by both electric and magnetic fields.
- Their wavelength, frequency and speed are linked by *c* = Î» f.

  They vary in wavelengths and frequencies. They behave differently in different media depending on their wavelengths or frequencies.

Radio waves

Radio waves have the longest wavelength and lowest frequency or energy in the family of waves. The wavelengths of radio waves vary between few centimetres to thousands of metres.

- **Sources:** Radio, T.V. and microwave transmitters; radio waves are produced when an electron moves up and down in the aerials of T.V. and radio transmitters. It is also produced by thunderstorm.

- **Detection:** Radio waves cannot be detected directly by the human ear but can be detected by radio and T.V. receivers fitted with aerials.
- **Uses:** Radio waves are used in radio and T.V. communication. Microwaves, UHF waves and VHF waves are examples of radio waves.

Microwaves

Of all the radio waves, microwaves have the shortest wavelength. ***Microwaves have shorter wavelengths than the radio waves but have higher frequencies and greater penetrating power.***

- **Sources:** Microwave ovens and hot objects produce microwaves.
- **Detection:** T.V. receivers and radar detect microwaves.
- **Uses:** Microwave beam stores or transmits more information than telephone lines. Radars use microwaves to detect the presence of enemy planes. Microwave ovens are used in cooking, microwaves penetrate food and cause it to cook faster than normal ovens. It has an additional advantage that food is cooked without the oven getting hot.

Infrared waves

Infrared waves are radiation emitted by hot objects with wavelengths in the range of 10^{-4} m to 10^{-6} m. These ranges of wavelengths are found next to red light in the visible spectrum.

- **Sources:** All hot or warm objects emit infrared radiation. The hotter the object, the more infrared (energy) it emits.
- **Detection:** The skin, a thermometer with blackened bulb and phototransistor, detect infrared radiation.
- **Uses:**

(i) Infrared heater is used to dry paints in the automobile industry.

(ii) Infrared cookers are used in cooking food.

(iii) Infrared is used to take photographs of objects in the dark.

(iv) Infrared is used to see through dust, mist and fog.

(v) Infrared is used in remote control to operate electronic devices.

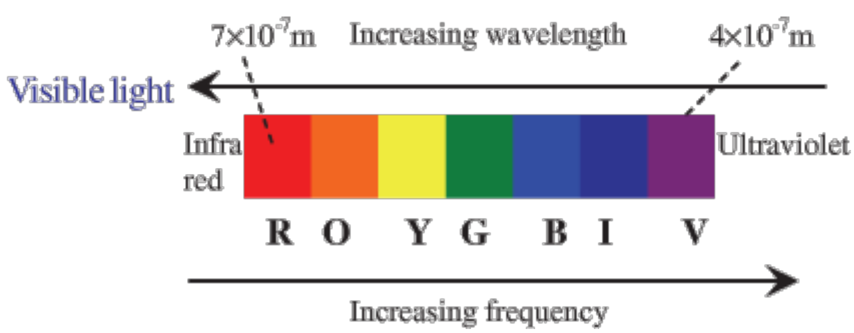


Figure 2.16: Visible light

The visible light are the ranges of wavelengths from 3.8 Ã— 10^{-7}m to 7.6 Ã— 10^{-7} m. The longest wavelength the eye can detect gives a sensation of red while the shortest wavelength gives a sensation of violet.

- **Sources:** Hot objects like the Sun and fluorescent materials emit visible light. The origin of light is the transition of electrons from one energy level to another.
- **Detection:** The eye, photographic films and photoelectric cells detect visible light.
- **Uses:** Visible light helps us to see things and to take photographs of objects. Visible light is the only part of the electromagnetic spectrum that can be seen.

Ultraviolet rays

Ultraviolet radiation is found beyond the violet end of the visible spectrum. The wavelengths of ultraviolet radiations range from 10^{-7} m to 10^{-8} m. The wavelength of u-v radiation is shorter

than that of the violet in the visible spectrum but the frequency and energy are higher. Ultraviolet radiation is harmful to the human eye and should not be looked upon directly. UV rays also cause suntan and large amounts can cause cancer.

- **Sources:** Very hot objects, the Sun, sparks u-v lamps and electric arc welding emit ultraviolet radiation .
- **Detection:** Photographic films and florescent materials detect ultraviolet radiation.
- **Uses:** Ultraviolet light makes some materials to glow (florescence). The chemicals are used in washing powder to make clothes very white.

Small amounts in your skin produce vitamin D. Most of the sunâ€™s UV rays are absorbed by the ozone layer in the atmosphere.

X-rays

X-rays are electromagnetic radiations of very short wavelengths and high penetrating power (high frequency). The wavelength of X-rays varies between 10^{-9} m to 10^{-11} m.

- **Source:** X-ray tubes produce X-rays when high-energy electrons strike a metal target and give up some of its energy. ***The origin of X-rays is the transition of electrons from higher energy levels to lower energy levels.***
- **Detection:** Photographic films and Geiger-Muller tube detect X-rays.
- **Uses:**

  (i) X-rays are used in the industry to detect cracks in welded joints, castings and wings of aeroplanes.

  (ii) X-rays are used in science to discover the arrangements of atoms in crystals.

  (iii) X-rays are used in medicine to reveal broken bones and to kill cancer cells.

Gamma rays

Gamma rays are electromagnetic radiations of very short wavelengths. They have the shortest wavelength and highest frequency (high penetrating power) in the electromagnetic spectrum. The typical wavelength is about 10^{-12}m.

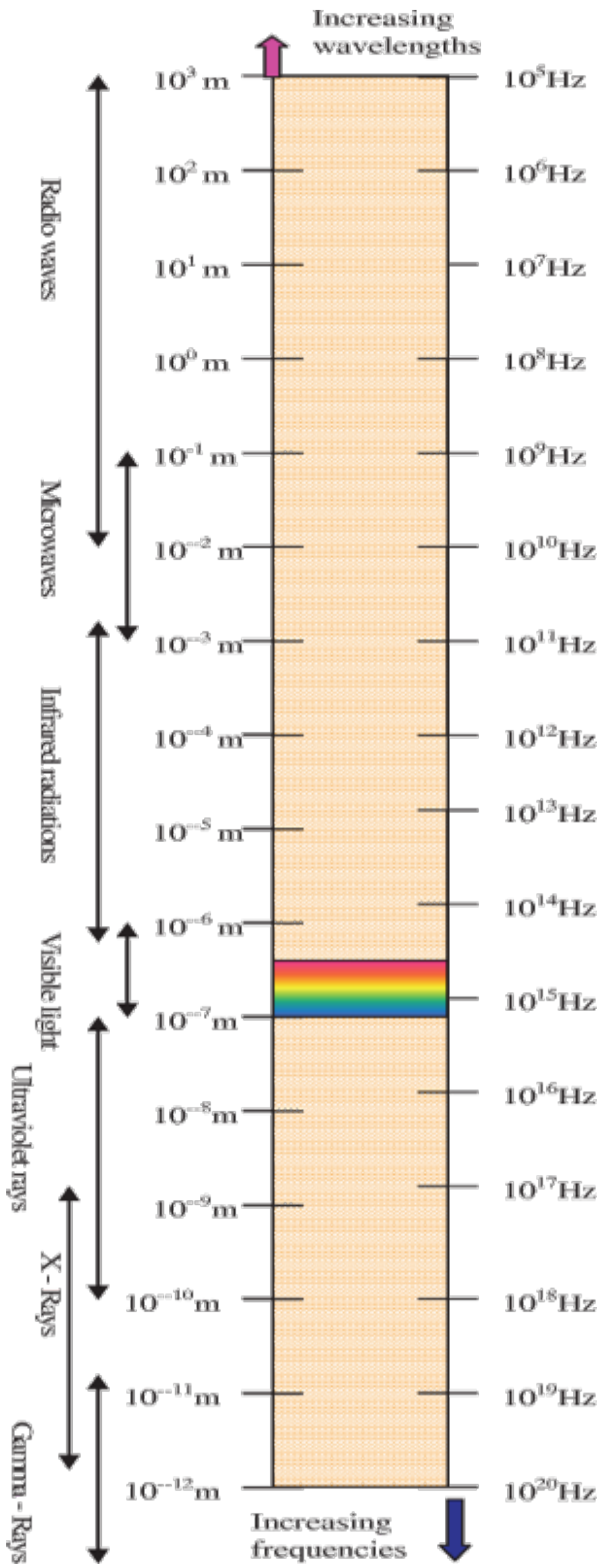


Figure 2.17 Electromagnetic spectrum

- **Source:** Gamma rays are given out during the decay of radioactive nuclide like uranium.
  The origin is the change in the structure of the nucleus of an atom.
- **Detection:** Photographic film and Geiger-Muller tubes detect gamma rays.
- **Uses:** Gamma rays are used in hospitals to sterilize syringe needles and other medical

equipment. It is also used to kill cancerous cells if administered with great care.

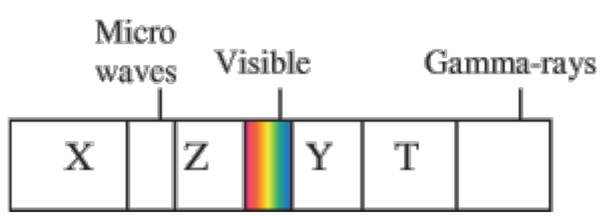
The electromagnetic spectrum is shown in Figure 14.12. The figure shows that the ranges of each wave are interwoven with no clear demarcation. X-rays and gamma rays only differ in their origin and penetrating power.

Summary

- Electromagnetic waves are electric field and a magnetic field vibrating at right angle and independent to each other and to the direction the wave is travelling. The range of wavelengths within this family of waves is called electromagnetic spectrum.
- Electromagnetic waves consist of radio waves, microwaves, infrared, visible light, ultraviolet, X-rays and gamma rays arranged in descending order of wavelengths.
- Radio waves have the longest wavelength and lowest frequency or energy in the electromagnetic spectrum.
- Infrared waves are radiation emitted by hot objects with wavelengths next to red light in the visible spectrum.
- Ultraviolet radiation is found beyond the violet end of the visible spectrum.
- X-rays are electromagnetic radiations of very short wavelengths and high penetrating power (high frequency).
- Gamma rays are electromagnetic radiations of very short wavelengths. They have the shortest wavelength and highest frequency (high penetrating power) in the electromagnetic spectrum.

Practice questions 2b

1. The diagram below shows the spectrum of electromagnetic radiation. Use the diagram to answer the following questions.



   (a) Identify the radiations X, Z, Y and T.

   (b) State the **source, means of detection** and **uses** of Z and T.

   (c) Explain why the radiation T has greater penetrating power than Z.

2. X-rays, gamma rays, microwaves, visible light, ultraviolet, radio waves and infrared.

   (a) Arrange the radiations in ascending order of penetrating power.

   (b) Arrange the radiations in ascending order of wavelength.

   (c) Arrange the radiations in ascending order of frequency.

3. (a) State the properties common to all electromagnetic waves.

   (b) State two properties that distinguish light waves and radio waves.

(c) Estimate the frequency of an X-ray radiation of wavelength 2.5 Ã— 10^{-10} m if the speed of the wave is 3.0 Ã— 10^{8} m s^{-1}.

4. (a) Explain what is meant by **electromagnetic waves** and **electromagnetic spectrum.**

(b) List in the descending order of wavelength the spectrum of electromagnetic waves.

(i) Identify the region of higher **energy** and **frequency.**

(ii) Identify the region sensitive to the human eye.

5.P and Q are two radiations at the ends of the visible spectrum of white light.

(i) What do P and Q represent?

(ii) How are P and Q identified?

(iii) Copy the diagram and show on it regions of higher frequencies.

(iv) State **two** uses of radiation P.

6.Which of the waves have the highest frequency?

A. Microwaves

B. Radio waves

C. X-rays

D. Infrared waves

7.Which of the following is **not** true of electromagnetic waves?

A. They are transverse in nature.

B. They travel through air with the same speed.

C. They consist of electric field and magnetic field vibrating perpendicular to each other and to direction of wave motion.

D. They are deflected by electric and magnetic waves.