

Chapter # 08

Physical Optics and Gravitational Waves

STUDENT'S LEARNING OUTCOMES (SLO's)

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

- Explain that polarization is a phenomenon associated with transverse waves.
- Define and apply Malus's law $I = I_0 \cos^2 \theta$ to calculate the intensity of a plane-polarized electromagnetic wave after transmission through a polarizing filter or a series of polarizing filters.
[Calculation of the effect of a polarizing filter on the intensity of an unpolarized wave is not required].
- Explain the use of polaroids in sky photography and stress analysis of materials.
- Describe qualitatively gravitational waves
[as waves of the intensity of gravity generated by the accelerated masses of an orbital binary system that propagate as waves outward from their source at the speed of light].
- State that as a gravitational wave passes a body with mass distortion in space-time can cause the body to stretch and compress periodically.
- State that gravitational waves pass through the Earth due to far off celestial events, but they are of very minute amplitude.
- Describe the use of interferometers in detecting gravitational waves.
[Interferometers are very sensitive detection devices that make use of the interference of laser beams (working and set up details are not required) and were used to first detect the existence of gravitational waves].

8.1 POLARIZATION OF LIGHT



1. What is meant by polarization? Explain that polarization is a phenomenon associated with transverse waves.

Ans. Polarization

Definition

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

Explanation

Interference and diffraction effects prove the wave nature of light. These phenomena, however, do not tell us whether the light waves are longitudinal or transverse. Polarization of light suggests that the light waves are transverse in nature.

In transverse mechanical waves, such as produced in a stretched string, the vibrations of the particles of the medium are perpendicular to the direction of propagation of the waves. The vibrations can be confined along vertical, horizontal or any other direction; Fig. 1. In each of these cases, the transverse mechanical wave is said to be polarized. The plane

of polarization is the plane containing the direction of vibration of the particles of the medium and the direction of propagation of the wave.

A light wave produced by oscillating charge consists of a periodic variation of the electric field vector E accompanied by the magnetic field vector B at right angles to it. Ordinary light has components of vibration in all possible planes. Such a light is unpolarized. On the other hand, if the vibrations are confined only in one plane, the light is said to be polarized. Unpolarized light; Fig. 2.

Examples of unpolarized light sources are sunlight, incandescent light bulbs, fluorescent light bulbs, light from a candle or fire.

Polarization of electromagnetic waves refers to the orientation of the electric field vector of the wave as it propagates through space.

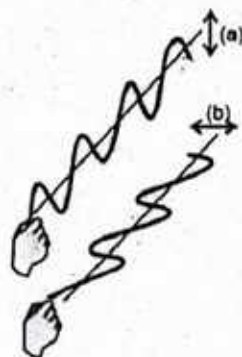


Fig. 1: Transverse waves on a string polarized (a) in a vertical plane, and (b) in a horizontal plane



Fig. 2: An unpolarized light, due to incandescent bulb, has vibrations in all planes.

Electromagnetic waves consist of oscillating electrical magnetic fields that are perpendicular to each other and to the direction of wave propagation. Polarization specially describes the behaviour of the electric field.



2. How can an unpolarized light be polarized? Explain.

Ans. How an unpolarized light be polarized?

Polarized Light

Vibrations of the electric field occur in a single plane perpendicular to the direction of wave propagation.

Example: Light reflected from water or glass surfaces can become partially polarized.

Unpolarized Light

Vibrations of the electric field occur in random direction of wave propagation.

Examples: Sunlight, incandescent bulbs, and most natural light sources emit unpolarized light.

An unpolarized light can be made polarized by the following methods:

1. Passing light through a polarizing filter (e.g., polaroid sheet).
2. Using a polarizing beam splitter.
3. Employing certain optical crystals or materials (e.g., calcite, quartz, etc.).

The most common method by which an unpolarized light can be polarized is by passing it through a polarizing filter, such as a polarizing beam splitter or a polaroid sheet. When an unpolarized light passes through the polarized filter, only that electric field vector which is parallel to the axis of polarized filter can pass through it, while all other vectors are blocked. The resultant light then becomes polarized; Fig. 3.

Thus, in simple words, the process of transforming an unpolarized light into a polarized light is said to be polarization.

Note: The orientation of the electric field vector E of light waves in a specific direction is the basis of Polarization.

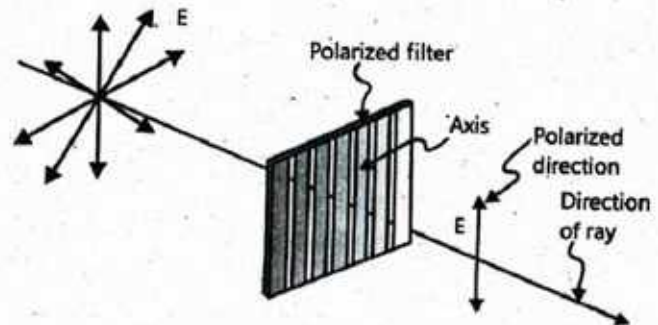


Fig. 3: Polarization of light using a polarized filter

8.2 TYPES OF POLARIZATION



3. State some basic types of polarization of light.

Ans. Types of Polarization:

Some basic types of polarization of light are:

1. Linear Polarization:

When the electric field vector oscillates in a single plane, light is said to be linearly polarized; Fig. 4(a). Example is the light passing through a polarizing filter, like sunglasses.

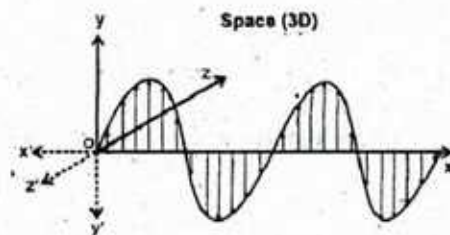


Fig. 4 (a) : Linear polarization of light

2. Circular Polarization

When the electric field rotates circularly, either clockwise (right-handed), or counterclockwise (left-handed), the light is said to be circularly polarized; Fig. 4(b). Example is the light reflected off a CD (Compact Disc) or DVD (Digital Versatile Disc).

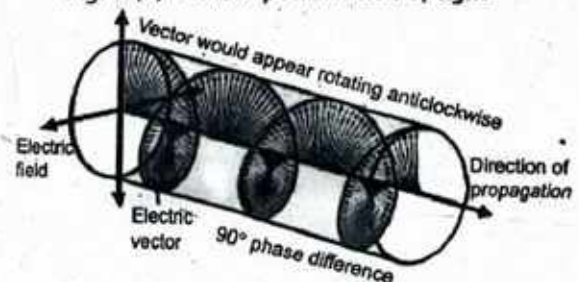


Fig. 4 (b) : Circular polarization of light

3. Elliptical Polarization

A combination of linear and circular polarization, where the electric field vector traces an elliptical path is called elliptical polarization. In elliptical polarization; Fig. 4(c), the two components of electric field E_x and E_y are not equal or they differ in phase by an arbitrary angle θ . Example is the light passing through a stress plate or a waveplate.

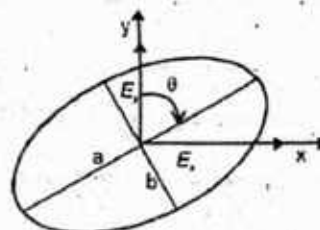


Fig. 4 (c): Elliptical polarization of light

8.3 PRODUCTION AND DETECTION OF PLANE POLARIZED LIGHT



4. How can the polarized light be produced and detected? What does it prove?

Ans. The light emitted by an ordinary incandescent bulb is unpolarized, because its electrical vibrations are randomly oriented in space; Fig. 2.

Experiment

If unpolarized light is made incident on a sheet of polaroid (polarizer), the transmitted light will be plane polarized. If a second sheet of polaroid (analyzer) is placed in such a way that the axes of the two polaroids shown by straight lines drawn on them are parallel; Fig. 5(a), the light is transmitted through the second polaroid. If the second polaroid (analyzer) is slowly rotated about the beam of light as axis of rotation, the light emerging from the second polaroid gets dimmer and dimmer and ultimately disappears when the axes become mutually perpendicular; Fig. 5(b), the light reappears on further rotation and becomes brightest when the axes are again parallel to each other.

This experiment proves that light waves are transverse waves. If the light waves were longitudinal, they would never disappear even if the two polaroids were mutually perpendicular.

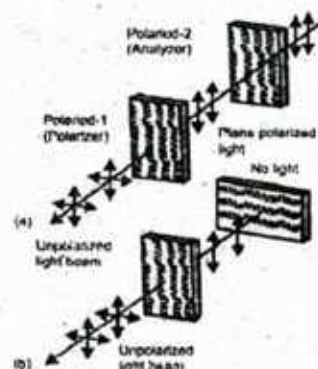
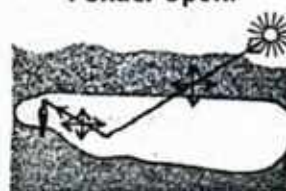


Fig. 5: Experimental arrangement to show that light waves are transverse. The lines with arrows indicate electric vibrations of light waves.

Ponder Upon!



Light reflected from smooth surface of water is partially polarized parallel to the surface.

8.4 POLARIZATION OF LIGHT BY THE METHOD OF REFLECTION



5. How can polarized light be obtained by the method of reflection? Explain.

Ans. In 1808, Malus discovered that polarized light is obtained when ordinary light is reflected by a plane sheet of glass.

Explanation

If the reflected light is viewed through a polaroid which is slowly rotated about the line of vision, the light is practically extinguished at a certain orientation of the polaroid. The most suitable angle of incidence ' i ' is about 57° for glass for which the reflected ray becomes plane polarized, as illustrated by ray diagram; Fig. (6). This proves that the light reflected by the glass is practically plane polarized. Light reflected from the surface of a table becomes darker when viewed through a rotated polaroid, showing that it is partially plane polarized.

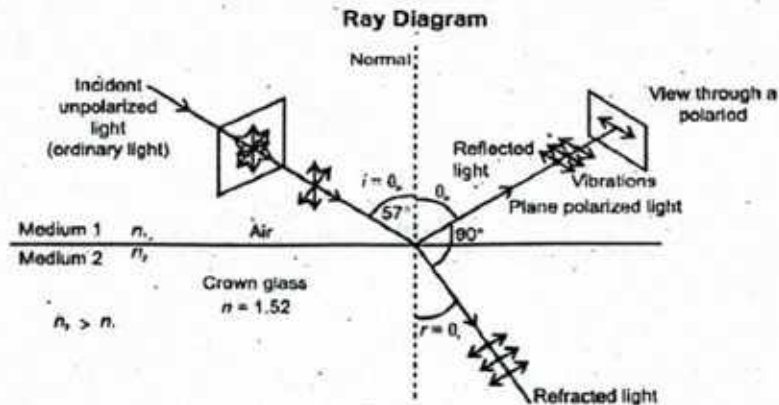


Fig. 6: Plane polarization by reflection

At a specific angle of incidence, called the Brewster's angle, the reflected light is completely plane polarized, meaning the electric field oscillates in a single direction, perpendicular to the plane of incidence.

Brewster's Law:

The particular angle of incidence on a transparent medium when the reflected light is almost plane polarized is called the polarizing angle.

Let a beam of unpolarized light be made incident on the surface of medium 2; Fig. 6. If the reflected beam of light is almost plane polarized, the reflected and refracted beams are at right angles to each other at the polarizing angle, $i = \theta_p$. Thus

$$\theta_p + \theta_r = 90^\circ$$

or $\theta_r = 90^\circ - \theta_p$

From Snell's law,

$$n_1 \sin \theta_p = n_2 \sin \theta_r$$

$$n_1 \sin \theta_p = n_2 \sin (90^\circ - \theta_p)$$

$$n_1 \sin \theta_p = n_2 \sin \theta_p$$

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

$$\tan \theta_p = \frac{n_2}{n_1}$$

This equation is known as Brewster's law.

In this equation, n_1 is refractive index of medium 1 and n_2 is refractive index of medium 2. If medium 1 is air, then equation becomes $\tan \theta_p = n$ because $n_1 = 1$ and $n_2 = n$. Here n is refractive index of medium on which light is incident. Hence, Brewster proved that the tangent of the angle of polarization is numerically equal to the refractive index of the medium 2 when medium 1 is air.

In Brewster's law, the angle ' θ_p ' for which the reflected ray and the refracted ray make an angle of 90° between them, is also called the Brewster angle θ_B . Then, $\tan \theta_B = n$ holds.

Example 8.1: A beam of light strikes the surface of a plate of glass with a refractive index of $\sqrt{3}$ at the polarizing angle. What will be the angle of refraction of the wave of light?

Solution:

Given that:

$$n = \sqrt{3}$$

To Find:

$$\theta_r = ?$$

Calculations:

As $\tan \theta_B = n$

or $\theta_B = \tan^{-1}(\sqrt{3})$

$$\theta_B = 60^\circ$$

As $\theta_r = 90^\circ - \theta_B$, $\theta_r = 90^\circ - 60^\circ$

$$\theta_r = 30^\circ \text{ Ans.}$$

Interesting Information

Malus's law is used to study the polarization of light in biological systems, such as the polarization of light by cell membranes.



6. State Malus's law. Explain the intensity formula.

Ans. Malus's Law

Statement

- It states that the intensity of plane polarized light after passing through an analyzer is directly proportional to the square of the cosine of the angle between the transmission axis of the analyzer and polarizer.

Mathematically;

$$I \propto \cos^2 \theta$$

$$I_o = I_o \cos^2 \theta$$

where I_o = Intensity of the incident polarized light.

Explanation

Malus's law gives a mathematical relation between the intensity of the light incident on the first polaroid (i.e., polarizer) and the intensity of light obtained after passing it through the second polaroid (i.e., analyzer). This is shown in Fig. 7(a). An analyzer is also a polarizer that is placed after a polarizer. Rotation of the analyzer affects the intensity of the polarized light. It is used to further reduce the intensity of light and also adjust it by adjusting the angle of the analyzer with respect to the polarizer.

Certain transparent crystalline materials, like tourmaline, calcite crystals, etc., are capable of confining vibrations of light waves in only one plane. Such materials are called polaroids which have high directionality in crystal structure. Light can also be polarized by natural phenomena like reflection, refraction and scattering.

If a piece of polaroid is rotated in front of a polarized ray of light, it causes a variation in the intensity of the light that gets through. The reason that causes the variation of intensity is the angle between the initial polarizer and the axis of second polarizer.

When the incident polarized light of amplitude A_o strikes the analyzer at an angle θ , it is resolved into two components $A_o \cos \theta$ and $A_o \sin \theta$; Fig. 7(b). The component $A_o \sin \theta$ is absorbed in the analyzer. Since, only $A_o \cos \theta$ passes through the analyzer, the amplitude A of the transmitted light is therefore,

$$A = A_o \cos \theta \quad \dots\dots\dots (i)$$

Since intensity I is proportional to the square of the amplitude A , it can be expressed as:

$$I \propto A^2 \text{ or } I = kA^2$$

where $k = 1$, we can write; $I = A^2$

$$\text{or } I = A_o^2 \cos^2 \theta$$

$$I = I_o \cos^2 \theta \quad (\because I_o = A_o^2)$$

where I_o is the intensity of the incident polarized light.

There are two extreme conditions of θ followed by the above equation given as,

- If $\theta = 0^\circ$, then $I = I_o$. This means the intensity transmitted through the analyzer is equal to the initial light intensity that passes through the polarizer.
- If $\theta = 90^\circ$, then $I = 0$. This means the light is extinguished completely, i.e., no light is allowed to pass through the analyzer.

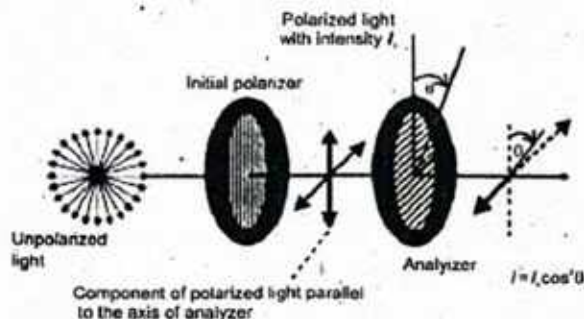


Fig. 7 (a) : Schematic representation of Malus's law

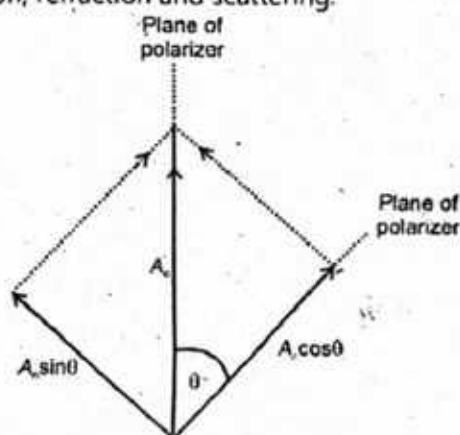
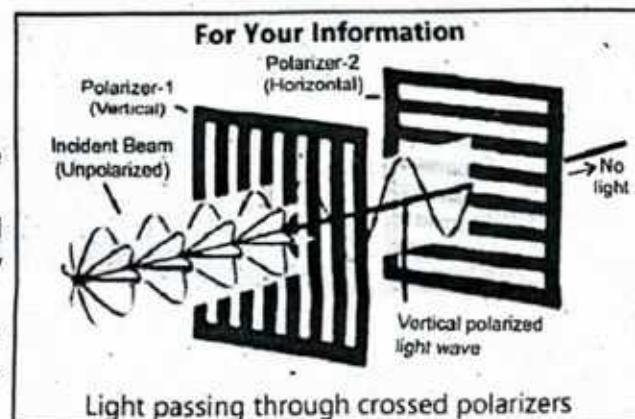


Fig. 7 (b) : Resolution of amplitude into components of plane polarization light.



For Your Information

Polaroid: It is a type of optical filter made from a special material that allows only light waves vibrating in a particular direction to pass through. It is commonly used to polarize light, which means, it blocks certain orientations of light waves.

Example: Polaroid sunglasses reduce glare by blocking horizontally polarized light.

Polarizer: A device or material that converts unpolarized light into polarized light by allowing only light vibrating in a specific direction to pass through.

Example: A polaroid sheet used in sunglasses acts as a polarizer.

Analyzer: It is a device used to detect and analyze polarized light.

Example: In a typical setup, when an analyzer is rotated, the intensity of transmitted light changes, helping measure the degree of polarization.



7. What is meant by optical activity? Discuss it in detail.

Ans. Optical activity is the ability of a substance to rotate the plane of polarization of polarized light as it passes through the substance.

Explanation

The rotation is detected with a polarizer or analyzer; Fig. 8. Many crystals and solutions rotate the plane of polarization of light passing through them. Such substances are said to be optically active. Examples are quartz crystals, cinnabar (HgS), sugar water, insulin and collagen.

Dependence of Direction of Rotation

The amount and direction of rotation depends on following factors:

- The type of substance
- The concentration of the substance (the amount of a substance present in a given quantity of a mixture or solution).
- The distance the light travels through it, and
- The wavelength of light.

Optical activity occurs due to the asymmetric shape of molecules in the substance, such as being helical. A few millimetre thickness of such crystals will rotate the plane of polarization by many degrees. Certain organic substances, such as sugar and tartaric acid, show optical rotation when they are in a solution. This property of optically active substances can be used to determine their concentration in the solutions.

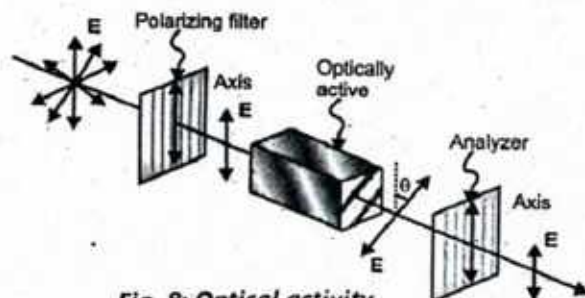
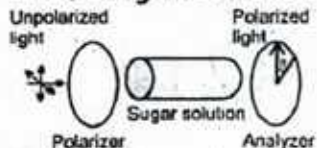


Fig. 8: Optical activity

Interesting Information



Sugar solution rotates the plane of polarization of incident light so that it is no longer horizontal but at an angle θ . The analyzer thus stops the light when rotated from the vertical (crossed) positions.

Example 8.2: Find the refractive index of a medium if polarizing angle is 54.5° .

Solution:

Given that;

$$\theta_p = 54.5^\circ$$

To Find:

$$n = ?$$

Calculations:

As $\tan \theta_p = n$

or $n = \tan \theta_p$

So $n = \tan 54.5^\circ$

$$n = 1.4 \text{ Ans.}$$

Do you know?



Looking through two polarizers when they are "crossed", very little light passes through.

Example 8.3: Polarized light with an intensity of 75 W m^{-2} passes through an analyzer with its axis at 30° to the polarizer's axis. What is the emerging intensity?

Solution:

Given that;

$$I_0 = 75 \text{ W m}^{-2}, \quad \theta = 30^\circ$$

To Find:

$$I = ?$$

Calculations: Using Malus's law:

$$I = I_0 \cos^2 \theta$$

$$I = 75 \text{ N m}^{-2} \cos^2 30^\circ$$

$$= 75 \text{ N m}^{-2} (0.866)^2$$

$$= 75 \text{ N m}^{-2} \times 0.75$$

$$I = 56.25 \text{ W m}^{-2} \text{ Ans.}$$

Example 8.4: A polarized light with an amplitude of 5 units passes through a polarizer with its electric field aligned at 60° to the original polarization direction. Find the amplitude of the wave after passing through the analyzer?

Solution:

Given that;

$$A_0 = 5 \text{ units}, \quad \theta = 60^\circ$$

To Find:

$$A = ?$$

Calculations: Using Malus's law:

$$A = A_0 \cos \theta$$

$$A = 5 \cos 60^\circ$$

$$= 5 \times 0.5$$

$$A = 2.5 \text{ units}$$

Tidbit

A beam of unpolarized light passes through a foggy atmosphere. Tell the polarization state of the scattered light.

Ans. When a beam of unpolarized light passes through a foggy atmosphere, the scattered light becomes partially polarized, especially when observed at a 90° angle to the direction of the incoming light.



8. What is the importance of polarization? Explain in detail.

Ans. Importance of Polarization

The significance of polarization of light may be justified by various fields such as:

1. Optics and Photonics

Polarization is essential for applications like polarized sunglasses, LCD (Liquid Crystal Display) screens, and optical communication systems.

2. Imaging and Microscopy

Polarization enhances image quality, reducing glare (unwanted light that interferes with vision) and improving contrast, especially in microscopy and medical imaging.

3. Medical Applications

Polarization is used in cancer diagnosis, tissue imaging, and laser surgery, leveraging its ability to distinguish between different tissue types.

4. Astronomy

Polarization helps us to analyze cosmic phenomena, like the polarization of light from distant stars or the cosmic microwave background radiation.

5. Miscellaneous Fields

Polarization has importance in miscellaneous fields such as optics and photonics, imaging and microscopy, biology and chemistry, communication system, etc.



9. Describe two main applications of polarization.

Ans. Two Main Applications of Polarization

Polarizers, also known as polarizing filters, have two main applications:

1. Sky Photography

A camera which is used to photograph the clouds is fitted with a polaroid. The light coming from the sky is polarized by the polaroid. In sky photography, polarizers are used to reduce the glare and haze which are produced by the scattering of light by small particles of molecules present in the atmosphere. Polarizers also enhance the contrast by blocking the excessive bright white light while allowing the other colours to pass through, thus creating a brighter detailed image. Thus, allows to improve the overall image quality.

2. Stress Analysis of Materials

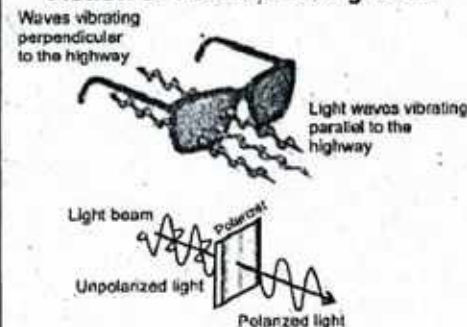
In materials science, polarizers are used to analyze the stress and strain on materials, such as plastics, metals, and glass.

When a material is stressed, its molecular structure changes, affecting the way, it interacts with light, and interference patterns on fringes are formed which in turn gives qualitative information about the material. By shining polarized light through the transparent material and analyzing the changes in the light's polarization, the researchers can:

- determine the material's stress patterns
- identify potential weaknesses or defects
- analyze the material's optical properties
- understand how the material will behave under different conditions. This technique is known as "photoelasticity" and is widely used in fields like engineering, materials science, and quality control.

In both cases described above, polarizers play a crucial role in manipulating light to achieve specific goals, whether it is enhancing image quality or analyzing material properties.

Action of Polarized Sunglasses



mqs

1. Which of the following types of waves can be polarized?

- (A) Sound waves (B) Light waves ✓
(C) Longitudinal waves (D) All of these

2. Polarization proves that light is:

- (A) A longitudinal wave (B) A scalar quantity
(C) A transverse wave ✓ (D) An electromagnetic wave

3. When unpolarized light is incident on an ideal polarizer, the intensity of the transmitted light is:

- (A) The same as the incident light
(B) Half of the incident light ✓
(C) One fourth of the incident light
(D) Zero

4. Which of the following devices can be used to polarize light?

- (A) Prism (B) Convex lens
(C) Polaroid sheet ✓ (D) Plane mirror

5. Which phenomenon is not associated with polarization of light?

- (A) Reflection (B) Refraction
(C) Scattering (D) Diffraction ✓

6. Polarized Sunglasses are used because they:

- (A) Block all light
(B) Allow only longitudinal light
(C) Reduce glare by blocking horizontal light ✓
(D) Magnify incoming light

7. When two polaroids are placed such that their transmission axes are at 90° to each other, the intensity of transmitted light is:

- (A) Maximum (B) Half
(C) Zero ✓ (D) Double

8. Light is said to be polarized when:

- (A) Its amplitude is reduced
(B) Its frequency remains constant
(C) Its electric field vibrates in only one direction ✓
(D) It travels in a single direction

9. In which phenomenon does the vibration of light occur in multiple planes?

- (A) Polarized light (B) Unpolarized light ✓
(C) Circularly polarized light (D) Plane-polarized light

10. The phenomenon used in sunglasses and camera filters to reduce glare is:

- (A) Reflection (B) Refraction
(C) Diffraction (D) Polarization ✓

11. Brewster's angle is defined as the angle of incidence at which:

- (A) Refraction ceases (B) Reflection is zero
(C) Reflected and refracted rays are parallel ✓
(D) Light becomes monochromatic

12. The angle of incident for which the reflected light is completely polarized is called:

- (A) Critical angle (B) Glancing angle
(C) Refraction angle (D) Brewster's angle ✓

13. If the refractive index of a medium is 1.5, the Brewster's angle is:

- (A) 45° (B) 56.3° ✓
(C) 30° (D) 60°

14. Malus's law is applicable to:
 (A) Refraction (B) Diffraction
 (C) polarized light ✓ (D) Monochromatic light
15. Malus's law is given by
 (A) $I = I_0 \sin^2 \theta$ (B) $I = I_0 \cos^2 \theta$ ✓
 (C) $I = I_0 \tan^2 \theta$ (D) $I = I_0 (1 + \cos \theta)$
16. At Brewster's angle, the reflected light is:
 (A) Completely unpolarized (B) Circularly polarized
 (C) Partially polarized (D) Completely plane polarized ✓
17. A light wave vibrating in more than one plane is called:
 (A) Unpolarized light ✓ (B) Polarized light
 (C) Plane polarized light (D) Linearly polarized light
18. Unpolarized light can be converted into polarized light by
 (A) Reflection (B) Refraction
 (C) Scattering (D) All of these ✓
19. Brewster's law is given by the equation:
 (A) $\tan \theta_B = \frac{n_2}{n_1}$ ✓ (B) $\sin \theta_B = \frac{n_2}{n_1}$
 (C) $\theta_B = \frac{n_2}{n_1}$ (D) $\cos \theta_B = \frac{n_1}{n_2}$
20. What happens when plane-polarized light passes through an analyzer rotated at 90° to the polarizer?
- (A) Light is intensified at 90°
 (B) Light is completely blocked ✓
 (C) Light becomes circular polarized
 (D) Light passes through unchanged
21. Brewster's law relates the angle of incidence to:
 (A) Wavelength of light (B) Frequency of light
 (C) Refractive index ✓ (D) Angle of deviation
22. According to Brewster's law, the reflected and refracted rays are:
 (A) Parallel (B) Perpendicular ✓
 (C) at 45° (D) Collinear
23. According to Malus's law, when the polarizer and analyzer are perpendicular, the transmitted intensity is:
 (A) Maximum (B) Half of original
 (C) Zero ✓ (D) Double
24. Malus's law deals with:
 (A) Intensity of reflected light
 (B) Intensity of polarized light passing through an analyzer ✓
 (C) Frequency of light
 (D) Wavelength of polarized light

8.6 GRAVITATIONAL WAVES (GWs)



10. What are gravitational waves? How are these waves detected?

Ans. Definition: "Ripples in the fabric of space-time, produced by violent cosmic events, like colliding black holes or neutron stars that travel at the speed of light, carrying information about their source."

A gravitational wave is a stretching and compressing of space-time and can be observed by measuring the change in length between two objects.

Example: The simplest example to understand GWs is given below:

If we throw a stone into a pond, the stone creates ripples on the water surface (space-time). These ripples travel outward, carrying information about the stone (the cosmic event). They can be detected on the shore by (gravitational wave observatories), revealing the stone's presence and properties.

Prediction and Detection

Gravitational waves are a prediction of Einstein's theory of general relativity which is confirmed by observations and is opening a new window into the universe's most extreme phenomena.

According to Einstein's general theory of relativity, gravity is not a force, but a curvature of space-time caused by massive bodies. Gravity is like a dent in a mattress. Heavy things warp the space around them, and that is why we feel gravity.

Gravitational waves, as initially predicted by Albert Einstein in 1916, are ripples in space-time that were first detected in 2015, but announced in 2016, the first observation of its kind: the detection of gravitational waves, produced from two colliding neutron stars. In this type, there is a gradual increase in frequency and amplitude of GWs.

A Binary System (BS) in the context of gravitational waves refers to "a system consisting of two compact objects, such as black holes, neutron stars, or white dwarfs, which are orbiting each other and emitting gravitational waves."



11. Describe some basic types of gravitational waves.

Ans. Four Basic Types of GWs

There are four basic types of gravitational waves, each with different sources and characteristics:

1. Continuous GWs

When a single massive object spins with a constant rate, such as a neutron star, continuous GWs are produced with a constant frequency and amplitude. White dwarf binary systems produce continuous GWs.

2. Compact Binary Inspirational GWs

When a binary system, such as binary neutron stars, binary black holes, or a neutron star and black hole orbiting each other, compact inspirational GWs are produced.

3. Burst GWs

These are produced by violent events like supernovae, gamma-ray bursts, or cosmic strings.

4. Stochastic GWs

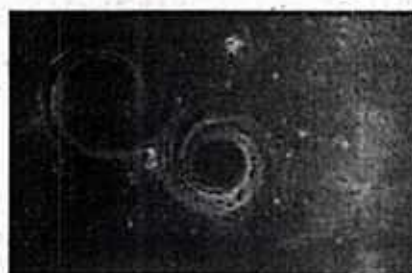
Stochastic GWs are weak, random signals of GWs which are produced by superposition of many weak gravitational wave sources, such as distant binary systems. These GWs are the most difficult to detect.



BS Model



Picture of a series of concentric spheres, with the binary system at the center, radiating gravity waves outward into the cosmos.



Tidal forces carry the mathematical signature of gravitational waves



12. What is meant by space-time distortion / tidal forces?

Ans. Space-time Distortion / Tidal Forces

Gravitational waves passing through a body with mass can cause the body to experience periodic stretching and compressing, also known as "space-time distortion". This effect is known as "tidal forces" and is a result of the gravitational wave's oscillating nature. As the gravitational wave passes through the body, it causes the space-time around the body to oscillate, leading to a periodic stretching and compressing of

the body in the direction perpendicular to the wave's propagation. This effect is similar to how the tides on Earth are caused by the gravitational pull of the Moon and Sun.

The amount of stretching and compressing depends on the strength of the gravitational wave, as well as the mass and size of the body. This effect is an important prediction of Einstein's general theory of relativity. Gravitational waves generated by far off celestial events, such as the merger of two black holes or neutron stars, pass through the Earth. However, the amplitude of these waves is extremely small, typically of the order of 10^{-21} to 10^{-22} metres. This means that the distortion caused by the gravitational wave is

incredibly tiny, and requires extremely sensitive instruments to detect.

Despite their small amplitude, gravitational waves offer a unique window into the universe, allowing us to study strong-field gravity, to test general relativity, and to explore the universe in ways previously impossible.



Spacetime curve of an artificial and a natural satellite



Spacetime curve shown by two satellites



13. What is LIGO interferometer? How does LIGO interferometer differ from a conventional interferometer?

Ans. An interferometer is an optical tool used in detecting gravitational waves. It is a very sensitive detection device that may use the interference of LASER (Light Amplification by Stimulated Emission of Radiation) beams.

An interferometer that detects gravitational waves is a highly sensitive instrument that uses LASER light to measure tiny changes in distance between mirrors, caused by gravitational waves passing through the detectors. These interferometers are called LIGO (LASER Interferometer Gravitational Wave Observatory). The main differences between LIGO and conventional interferometers are:

- LIGO is 1000 times larger than conventional device, and
- LIGO uses LASER whereas conventional interferometer has normal light source.



14. Describe the basic LIGO interferometer in detail.

Ans. Basic Components of GW Interferometer

The basic components of a gravitational wave interferometer are:

- Laser** that produces a stable and high intensity beam of light.
- Power recycling mirror** continually reflects LASER light that has already travelled through the instrument back into the interferometer and hence the term recycling is used.
- Beam splitter** divides the LASER beam into two perpendicular beams.
- Mirrors** reflect the beams, creating two perpendicular arms.
- Fabry Perot cavity** consists of two mirrors facing each other. The purpose of the cavity is to enhance the path length.
- Photodetectors** measure the returning beams, detecting tiny phase shifts (if any).
- Arm cavities** enhance the LASER light, increasing sensitivity.

Working of Interferometer

A laser beam is split into two perpendicular beams, each travelling down two identical paths (arms) of the interferometer. The beams bounce off mirrors at the ends of each arm and return to the starting point, where they are recombined. If a gravitational wave passes through, it causes a tiny disturbance in the distance between the mirrors, resulting in a phase shift between the two beams.

When the beams recombine, they create an interference pattern, which is measured by a photodetector. The tiny phase shift caused by the gravitational wave alters the interference pattern, allowing the detector to sense the wave's presence.

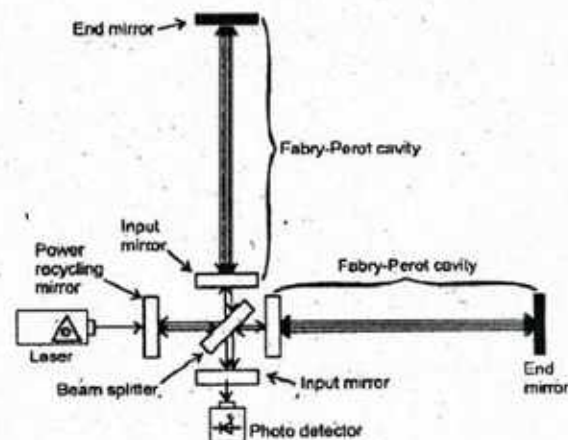


Fig. 9: Basic LIGO Interferometer

Virgo Detection

Similar to LIGO, there is another facility for measuring gravitational waves. This is called Virgo, which works under the European Gravitational Observatory (EGO) Cascina near Pisa, Italy. Virgo is also an interferometer with two arms of 3 km whereas LIGO has 4 km arms. The Virgo Observatory is named after the Virgo constellation, which is visible in the night sky during the months of March, April and May. The Virgo cluster is a group of about 1,500 galaxies about 50 MLYs (Million Light Years) away. Remember one Light Year (LY) is a distance which light travels in one year. The approximate value of 1 LY = 9.5 billion km. Virgo has been involved in detecting gravitational wave events, with the first detection in 2017.



15. From which sources gravitational waves be produced? Explain.

Ans. Every physical object that accelerates; produces gravitational waves. Vehicles, airplanes, etc. are included in it. The masses and acceleration of objects on the Earth are too small to make gravitational waves big enough to be detected with our instruments.

As the binary systems (also termed as binaries) orbit each other, they emit gravitational waves, which can be detected by observatories like LIGO (Laser Interferometer Gravitational wave Observatory) which is situated in USA and Virgo, a large scale gravitational wave observatory in Cascina, Italy. The waves carry information about the system's mass, spin, and merger dynamics, offering insights into these extreme cosmic objects, and move with the speed of light.

The binary systems are significant sources of gravitational waves, and their mergers (collision and union of two massive objects resulting more massive single object) are among the most intense cosmic events.

As the masses orbit and accelerate, their gravitational intensity fluctuates, generating waves that radiate outward in all directions. These waves are not bound by the binary system's gravity; instead, they travel freely through space-time at the speed of light. The waves propagate through the universe, weakening in intensity as they distance themselves from the source.

The characteristics of GWs depend on the system's properties, such as:

- Masses of the objects
- Orbital period and frequency
- Eccentricity of the orbit: Eccentricity e is a measure of the amount by which an object deviates from a perfect circle.

$e = 0$ Circular orbit

$e = 1$ Parabolic trajectory

$e > 1$ Hyperbolic trajectory

$0 < e < 1$ Elliptical orbit



Picture of a series of concentric spheres, with the binary system at the center, radiating gravity waves outward into the cosmos.



Tidal forces carry the mathematical signature of gravitational waves

Example 8.5: If the gravitational waves have a wavelength of 4000 km, find their frequency.

Solution:

Given that;

$$\lambda = 4000 \text{ km} = 4 \times 10^6 \text{ m}, \quad c = 3 \times 10^8 \text{ m s}^{-1}$$

To Find:

$$f = ?$$

Calculations:

As $v = f\lambda$

or $f = \frac{c}{\lambda} \quad (\because v = c)$

$$f = \frac{3 \times 10^8 \text{ m s}^{-1}}{4 \times 10^6 \text{ m}}$$

$$f = 0.75 \times 10^2 \text{ s}^{-1}$$

$$f = 75 \text{ Hz Ans.}$$

Example 8.6: A binary system emits gravitational waves with a frequency of 10^{-1} Hz. What is the wavelength of these waves?

Solution:

Given that;

$$f = 10^{-1} \text{ Hz} = 10^{-1} \text{ s}^{-1}, \quad c = 3 \times 10^8 \text{ m s}^{-1}$$

To Find:

$$\lambda = ?$$

Calculations:

$$\text{As } v = f\lambda$$

$$\text{or } \lambda = \frac{c}{f} \quad (\because v = c)$$

$$\therefore \lambda = \frac{3 \times 10^8 \text{ m s}^{-1}}{10^{-1} \text{ s}^{-1}}$$

$$\lambda = 3 \times 10^9 \text{ m Ans.}$$



- | | |
|---|---|
| <p>1. Gravitational waves are caused by
 (A) Changes in magnetic fields
 (B) Acceleration of charged particles
 (C) Acceleration of massive objects ✓
 (D) Decay of radioactive elements</p> <p>2. What is the nature of gravitational waves?
 (A) Longitudinal waves in space-time
 (B) Transverse waves in space-time ✓
 (C) Sound waves in space
 (D) Circular waves in space</p> <p>3. What kind of wave is a Gravitational wave?
 (A) Electromagnetic (B) Mechanical
 (C) Quantum (D) Space-time distortion ✓</p> <p>4. Gravitational waves carry:
 (A) Only momentum (B) Only mass
 (C) Energy and momentum ✓
 (D) No physical quantities.</p> <p>5. Gravitational waves travel at the speed of:
 (A) Sound (B) Light ✓
 (C) Gravity (unknown) (D) Electricity</p> <p>6. Gravitational waves are difficult to detect because:
 (A) They are very rare
 (B) They only occur in the early universe
 (C) They travel slower than light
 (D) They produce extremely tiny distortions in space ✓</p> <p>7. Space-time distortion is caused by
 (A) Mass and energy ✓
 (B) Temperature differences
 (C) Sound waves and energy
 (D) Electric charge only</p> | <p>8. Tidal forces are most significant near:
 (A) The surface of the Earth
 (B) The moon
 (C) A white dwarf (D) A black hole ✓</p> <p>9. Which of the following best describes what happens to space-time near a massive object?
 (A) It remains flat (B) It becomes twisted
 (C) It becomes curved ✓ (D) It disappears</p> <p>10. Gravitational waves are ripples in:
 (A) Space (B) Time
 (C) Magnetic fields (D) Space-time ✓</p> <p>11. LIGO detects gravitational waves using principle of:
 (A) Reflection (B) Refraction
 (C) Laser interferometry ✓ (D) Doppler effect</p> <p>12. The LIGO detector splits laser light into two beams using a:
 (A) Prism (B) Lens
 (C) Diffraction grating (D) Beam splitter ✓</p> <p>13. When a gravitational wave passes through LIGO, it causes:
 (A) The mirror to heat up
 (B) The vacuum to collapse
 (C) A colour change in the laser
 (D) The arms to change length very slightly ✓</p> <p>14. Virgo uses to which technique to detect gravitational wave?
 (A) Radio telescope (B) X-ray reflection
 (C) Michelson interferometer ✓
 (D) cosmic microwave background analysis</p> |
|---|---|

ADDITIONAL SHORT ANSWER QUESTIONS


1. **What type of waves can be polarized?**

Ans. Only transverse waves, like light waves can be polarized.

Q.2 Give one practical application of polarization.

Ans. Polarized sunglasses reduce glare by blocking horizontally polarized light reflected from surface like water or roads.

Q.3 What happens when two polaroids are placed at 90° to each other?

Ans. No light passes through, the second polaroid blocks the polarized light from the first.

Q.4 What is a polaroid?

Ans. It is a material that allows only light vibrating in a specific direction to pass through, thus producing polarized light.

Q.5 Can sound waves be polarized? Why or why not?

Ans. No, sound waves cannot be polarized because they are longitudinal waves.

Q.6 Why is detection of plane polarized light important?

Ans. It confirms the transverse nature of light and is useful in applications like stress analysis and 3D movies.

Q.7 Name three methods to produce plane polarized light.

Ans. Polarization by reflection, refraction, and selective absorption (using polaroids).

Q.8 What is plane polarized light?

Ans. It is light in which the vibrations of the electric field occur in only one plane perpendicular to the direction of propagation.

Q.9 Name one practical use of Brewster's law.

Ans. It is used in making anti-glare sunglasses and camera lens filters.

Q.10 Can Brewster's law be applied to all type of waves?

Ans. No, it specially applies to transverse waves like light.

Q.11 Is Malus's law applicable to unpolarized light?

Ans. No, it only applies to plane-polarized light passing through an analyzer.

Q.12 How does Malus's law help in optics?

Ans. It is used to measure the degree of polarization and study the properties of polarized light.

Q.13 How do gravitational waves travel?

Ans. They travel at the speed of light through space-time.

Q.14 What causes gravitation waves?

Ans. They are caused by violent astrophysical events like binary black hole mergers, neutron star collisions, or supernovae.

Q.15 What is the effect of gravitational waves on matter?

Ans. They cause very tiny stretching and compressing of space in perpendicular direction as they pass through.

Q.16 How are gravitational waves detected?

Ans. They are detected by using highly sensitive laser interferometers, like LIGO and Virgo.

Q.17 Why are gravitational waves important in astronomy?

Ans. They provide a new way to observe and understand cosmic events that are invisible in electromagnetic radiation.

Q.18 What is LIGO?

Ans. LIGO (Laser Interferometer Gravitational-wave Observatory) is large-scale physics experiment designed to detect gravitational waves.

Q.19 Can gravitational waves be felt by humans?

Ans. No, their effects are extremely small and cannot be felt directly by humans.

Q.20 How do gravitational waves propagate?

Ans. They travel outward from their source at the speed of light ($3.0 \times 10^8 \text{ ms}^{-1}$).

Q.21 What is the purpose of LIGO?

Ans. LIGO is designed to detect gravitational waves from astronomical events like black hole or neutron star merger.

Q.22 How does LIGO detect gravitational waves?

Ans. LIGO uses laser interferometry to measure tiny changes in the length of its arm caused by passing gravitational waves.

Q.23 What is the basic principle behind LIGO?

Ans. It is based on the interference of light; gravitational waves slightly stretch and compress space, changing the path length of laser beams in the interferometer.

Q.24 What kind of astronomical information can Virgo provide?

Ans. It helps to determine the origin, distance, and nature of gravitational waves.

Q.25 How are tidal forces related to space-time distortion?

Ans. Tidal forces arise due to the non-uniform curvature of space-time near massive objects.

SOLVED EXERCISE

MULTIPLE CHOICE QUESTIONS

Tick (✓) the correct answer.

- 8.1 The phenomenon of polarization of light is:
(a) the process of scattering of light (b) the property of light to vibrate in a specific plane ✓
(c) the ability of light to travel in a straight line (d) the phenomenon of light changing colour
- 8.2 Malus's law states that:
(a) the intensity of light is directly proportional to the square of the cosine of the angle between the light wave and the analyzer ✓
(b) the intensity of light is directly proportional to the square of the sine of the angle between the light wave and the analyzer
(c) the intensity of light is directly proportional to the angle between the light wave and the analyzer
(d) the intensity of light is inversely proportional to the angle between the light wave and the analyzer
- 8.3 The intensity of light when it passes through a polarizer:
(a) increases (b) decreases ✓ (c) remains the same (d) becomes zero
- 8.4 The angle between the light wave and the analyzer is called:
(a) polarization angle ✓ (b) refraction angle (c) reflection angle (d) azimuth angle
- 8.5 The key purpose of an analyzer in a polarization experiment is:
(a) to polarize the light (b) to measure the intensity of light ✓
(c) to change the direction of light (d) to filter out unwanted light
- 8.6 The mathematical representation of Malus's law is:
(a) $I = I_0 \cos^2 \theta$ ✓ (b) $I = I_0 \sin^2 \theta$ (c) $I = I_0 \tan^2 \theta$ (d) $I = I_0 \cot^2 \theta$
- 8.7 The effect of increasing the angle between the light wave and the analyzer on the intensity of light is:
(a) the intensity increases (b) the intensity decreases ✓
(c) the intensity remains the same (d) the intensity becomes zero
- 8.8 The condition for maximum intensity of light in a polarization experiment is when:
(a) the light wave and analyzer are perpendicular (b) the light wave and analyzer are parallel ✓
(c) the light wave and analyzer are at an angle of 45° (d) the light wave and analyzer are at an angle of 60°
- 8.9 The unwanted light that interferes with vision is termed as:
(a) haze (b) glare ✓ (c) contrast (d) flare
- 8.10 Who predicted the existence of gravitational waves?
(a) Galileo Galilei (b) Albert Einstein ✓ (c) Issac Newton (d) Leonardo da Vinci
- 8.11 What are gravitational waves?
(a) Electromagnetic waves (b) Mechanical Waves
(c) Ocean waves (d) Ripples in the fabric of spacetime ✓
- 8.12 Which is the primary method used to detect gravitational waves?
(a) Optical telescopes (b) Radio telescopes (c) LASER interferometry ✓ (d) Gravitational lensing
- 8.13 Which of the following is a primary source of gravitational waves?
(a) Binary black hole merger ✓ (b) Solar flares
(c) Earthquake (d) Solar wind

SHORT ANSWER QUESTIONS

8.1. Why are the polaroid sunglasses better than the ordinary sunglasses?

Ans. Polaroid glasses, commonly known as polarized sunglasses, offer several advantages over ordinary (non-polarized) sunglasses, primarily due to their ability to reduce glare. Here is why they are considered better in many situations.

1. Glare Reduction

How it works: Polarized lenses have a special chemical coating that filters light. They block horizontally polarized light, which is the type of light that reflects off flat surfaces like water, roads, snow, and glass.

Benefit: This significantly reduces harsh glare, making it easier and more comfortable to see in bright conditions, especially around water, snow, or while driving.

2. Enhanced Visual Clarity and Contrast

(i) Polarized lenses improve contrast and visual clarity. Colors appear more vibrant and details sharper, which helps reduce eye strain over long periods.

(ii) This makes them ideal for activities like fishing, boating, skiing, hiking, and driving.

3. Reduced Eye Strain

By minimizing glare and improving clarity, polarized sunglasses reduce the constant squinting and effort your eyes need to adjust, which helps prevent headaches and eye fatigue.

4. Better Safety for Outdoor Activities

For activities like driving, cycling, or water sports, polarized lenses enhance visibility of road surfaces, obstacles, or changes in terrain, improving overall safety.

When Ordinary Sunglasses Might Be Preferred: While polarized glasses offer many benefits, there are situations where ordinary sunglasses might be more suitable.

LCD screens: Polarized lenses can make it hard to read screens on smartphones, tablets, GPS devices, or airplane instrument panels because they block some light emitted from these displays.

Pilots: Many pilots avoid polarized lenses because they interfere with viewing certain cockpit displays.

Snow sports: In specific conditions, polarized lenses might make it harder to distinguish icy patches on snow.

Conclusion: If you spend a lot of time outdoors, especially around reflective surfaces, polarized sunglasses are often the better choice due to superior glare reduction, improved comfort, and enhanced visual clarity. However, for general use, ordinary sunglasses can still provide good UV protection without the specific filtering effects of polarization.

8.2. Is light from the sky partially polarized? How is it so?

Ans. Yes, light from the sky is partially polarized. This phenomenon occurs due to Rayleigh scattering, which is the scattering of sunlight by molecules and small particles in the Earth's atmosphere.

How Does This Happen?

1. **Unpolarized Sunlight:** The light coming from the Sun is unpolarized, meaning its electric field vectors oscillate in all possible directions perpendicular to its direction of travel.

2. **Scattering by Air Molecules:** As sunlight enters the Earth's atmosphere, it interacts with gas molecules, dust, and other small particles. When these particles scatter the incoming light, they cause the oscillating electric field to realign in specific ways.

3. Polarization Effects

(i) **At 90° to the Sun:** The light scattered at 90 degrees relative to the incoming sunlight becomes strongly polarized. This happens because, at this angle, the scattered light's electric field tends to oscillate in a direction perpendicular to both the incoming sunlight and the line of sight of the observer.

(ii) **Other Angles:** At angles closer to the Sun (or directly opposite), the degree of polarization decreases. Direct sunlight (looking straight at the Sun) is unpolarized because it hasn't been scattered.

(iii) This effect is why polarizing filters can darken the sky in photographs. The filter blocks certain orientations of polarized light, enhancing contrast and reducing glare.

(iv) Many animals, like bees and some birds, can detect this polarization pattern, which helps them navigate using the sky.

8.3. How is Malus's law used in everyday life?

Ans. Malus's Law describes how the intensity of polarized light changes as it passes through a polarizing filter. The law is mathematically expressed as:

$$I = I_0 \cos^2\theta$$

Everyday Applications of Malus's Law:

1. Polarized Sunglasses

Polarized sunglasses reduce glare by blocking horizontally polarized light, which is commonly reflected from surfaces like water, roads, and car hoods.

Real-life example: When you tilt your head while wearing polarized sunglasses, you might notice changes in brightness due to the varying angle.

2. **Photography and Camera Filters**

Photographers use polarizing filters to control reflections and enhance contrast in images. By rotating the filter, they adjust the angle, controlling the intensity of reflected light based on Malus's law.

Real-life example: Capturing clearer images of the sky or water with reduced reflections.

3. **LCD Screens (Liquid Crystal Displays)**

LCD technology relies heavily on polarization. The screen has layers of polarizers, and liquid crystals control the polarization angle of light. The brightness of each pixel depends on how much light passes through these filters, following Malus's law.

Real-life example: If you wear polarized sunglasses and tilt your phone or laptop screen, you might notice changes in visibility because the polarization angles are misaligned.

4. **3D Glasses in Cinemas**

Many 3D movies use polarized light to create depth perception. Each lens of the 3D glasses filters light polarized in different directions. Malus's law governs how each eye receives different light intensities, creating the 3D effect.

Real-life example: Watching a 3D movie and noticing that removing the glasses results in a blurry double image.

5. **Stress Analysis in Transparent Materials (Photoelasticity)**

Engineers use polarized light to detect stress patterns in materials. When polarized light passes through a stressed material, the internal strain causes changes in polarization, and Malus's law helps analyze the resulting light intensity patterns.

Real-life example: Viewing colourful stress patterns in clear plastic items when looking through polarized lenses.

6. **Anti-Glare Coatings**

Screens and lenses with anti-glare coatings often manipulate light polarization to reduce reflections. Malus's law helps in designing these coatings to minimize light intensity from unwanted angles.

Real-life example: Reading from a Kindle or an anti-glare screen outdoors without annoying reflections.

In all these cases, Malus's law provides the mathematical foundation for understanding how light intensity changes with polarization, enabling technologies that improve vision, display quality, and material analysis.

8.4. **What are the applications of Brewster's angle?**

Ans. Brewster's angle, also known as the polarizing angle, is the angle of incidence at which light with a particular polarization is perfectly transmitted through a surface with no reflection. When unpolarized light hits a surface at Brewster's angle, the reflected light becomes completely polarized perpendicular to the plane of incidence. This phenomenon has several practical applications:

1. **Polarizing Filters**

- (i) **Photography:** Polarizing filters reduce glare and reflections from non-metallic surfaces like water, glass, and roads. They also enhance contrast and colour saturation in images.
- (ii) **Sunglasses:** Polarized sunglasses reduce glare from horizontal surfaces, improving visual comfort and clarity, especially for activities like driving, boating, and skiing.

2. **Optical Coatings**

- (i) **Anti-Reflective Coatings:** Optical devices like lenses and displays use coatings designed considering Brewster's angle to minimize unwanted reflections.
- (ii) **Laser Optics:** Brewster windows in laser cavities are oriented at Brewster's angle to allow maximum transmission of polarized laser light while minimizing reflection losses.

3. **Laser Technology**

- (i) **Polarization Control:** Lasers often require polarized beams. Brewster-angle components help produce or maintain the polarization of laser light efficiently.
- (ii) **Brewster Windows:** These are specially angled glass windows in gas lasers that allow polarized light to pass with minimal loss, improving the laser's efficiency.

4. **Telecommunications**

Fiber Optics: Brewster's angle principles are used to reduce signal losses in fiber-optic communication systems, where controlling light polarization is crucial for signal integrity.

5. **Microscopy and Optical Instruments**

Contrast Enhancement: Polarization techniques based on Brewster's angle are used in microscopy to enhance contrast when observing specimens, especially in reflective materials.

6. **Measurement of Refractive Index**

By measuring the Brewster's angle for a given material, its refractive index can be accurately calculated. This is a simple, non-destructive method widely used in optics labs.

7. **Display Technology**

Liquid Crystal Displays (LCDs): Polarizing filters, which rely on Brewster's angle, are key components in LCD screens to control light transmission and improve display clarity.

8. **Glare Reduction in Vehicles and Architecture**

Windshields and Windows: Special coatings designed based on Brewster's angle principles reduce glare, enhancing safety and comfort.

8.5. **What is the space-time curvature?**

Ans. Spacetime curvature is a fundamental concept in Einstein's general theory of relativity, which describes gravity not as a force but as the effect of the bending or warping of spacetime caused by mass and energy. According to this theory:

- (i) Spacetime is a four-dimensional fabric combining the three dimensions of space with time.
- (ii) Massive objects like stars, planets, and black holes cause this fabric to curve.
- (iii) The more massive the object, the greater the curvature it produces.

Objects moving through spacetime follow paths called geodesics, which are the straightest possible paths in curved space. What we perceive as the force of gravity is actually objects following these curved paths due to spacetime distortion.

A common analogy is placing a heavy ball on a stretched rubber sheet, causing a dip. Smaller balls placed nearby will roll towards the heavier one, not because of a direct pull, but because of the curved surface. Similarly, planets orbit stars because they move along the curves created in spacetime by the star's mass.

CONSTRUCTED RESPONSE QUESTIONS

8.1. **Write down some applications of plane polarized.**

Ans. Applications of Plane Polarized Light

1. **Polaroid Sunglasses**

- (i) Reduce glare from reflective surfaces like water, roads, and glass.
- (ii) Enhance visual clarity and comfort in bright conditions.

2. **Photography and LCD Screens**

- (i) Polarizing filters improve contrast and reduce reflections in photos.
- (ii) LCD technology relies on polarized light to control display brightness and colours.

3. **Stress Analysis in Transparent Materials (Photoelasticity)**

Used to detect stress distribution in materials by observing patterns under polarized light.

4. **Optical Mineralogy**

Identification of minerals and crystals in thin sections using polarizing microscopes.

5. **Chemical Analysis (Polarimetry)**

Measures optical rotation to determine the concentration and purity of chiral substances (e.g., sugars, amino acids).

6. **3D Movies and Projection Systems**

Utilize polarized glasses to separate images for each eye, creating a 3D effect.

7. **Laser Technology**

Polarized lasers are used in optical communication, cutting, and medical surgeries for precision.

Applications of Circularly Polarized Light

1. **3D Cinema Technology**

Circular polarization avoids image distortion when viewers tilt their heads, improving the 3D experience.

2. **Biological and Chemical Sensing**

Used to study chiral molecules and proteins, as it interacts differently with left- and right-handed enantiomers.

3. **Optical Communication**
Enhances data transmission efficiency and reduces interference in fiber-optic systems.
4. **Anti-Counterfeiting Measures**
Embedded in holograms on currency, credit cards, and official documents to prevent forgery.
5. **Microscopy (Circular Dichroism Spectroscopy)**
Analyzes structural properties of biomolecules like proteins and nucleic acids.
6. **Antenna Technology (Satellite Communication)**
Circularly polarized antennas maintain signal strength regardless of orientation changes between transmitter and receiver.
7. **Liquid Crystal Displays (Advanced Displays)**
Used in some advanced LCDs to improve contrast and viewing angles.

8.2. Would it be possible to use a polarizer as an analyzer? If yes, give at least two examples.

Ans. Yes, a polarizer can indeed be used as an analyzer. Both devices operate on the same principle of selectively transmitting light waves based on their polarization direction. While a polarizer is typically used to create polarized light, an analyzer is used to detect or analyze the polarization state of light.

Examples

1. Determining the Polarization of Light:

Setup: Place a polarizer (now acting as an analyzer) after light that may be polarized.

Observation: As you rotate the polarizer, the intensity of the transmitted light will change.

If the light is polarized, the intensity will vary from maximum (when the polarizer's axis aligns with the light's polarization direction) to zero (when perpendicular).

If the light is unpolarized, the intensity will remain constant regardless of the polarizer's orientation.

2. Stress Analysis in Transparent Materials (Photoelasticity):

Place a stressed transparent material between two polarizers (one acts as a polarizer, the other as an analyzer).

The stressed regions cause changes in polarization due to birefringence, producing colorful patterns when viewed through the analyzer.

This technique is used in engineering to visualize stress distribution in materials.

In both cases, the polarizer functions effectively as an analyzer by selectively transmitting specific polarization components, allowing analysis of the light's polarization state.

8.3. Explain how Malus's law is used in the design of polarized sunglasses. How do these surfaces reduce glare from reflective surface? Provide an example to illustrate your answer.

Ans. Malus's Law and Polarized Sunglasses

Malus's Law describes how the intensity of polarized light changes when it passes through a polarizing filter. It is mathematically expressed as:

$$I = I_0 \cos^2 \theta$$

Application in Polarized Sunglasses

Polarized sunglasses are designed with special filters that allow only light polarized in a specific direction to pass through. Typically, these filters are oriented to block horizontally polarized light, which is the primary cause of glare.

When sunlight reflects off flat surfaces like water, roads, or snow, it becomes partially polarized, with a strong horizontal component. This horizontally polarized light causes intense glare, making it difficult to see clearly.

Malus's law comes into play as follows:

1. **Glare Reduction:** The polarized lenses are designed with a vertical polarization axis. When horizontally polarized glare (from reflective surfaces) hits the lens, the angle between the glare's polarization direction and the filter's axis is 90° .

2. **Light Intensity Drop:** According to Malus's Law:

$$I = I_0 \cos^2 (90^\circ) = I_0 \times 0 = 0$$

This means the intensity of the glare is reduced to zero, effectively eliminating the harsh reflection.

3. **Normal Vision:** Light that is not polarized horizontally (like light from the sky or non-reflective objects) passes through with minimal reduction, maintaining clear vision.

Example: Driving on a Sunny Day

Imagine driving on a sunny day, and the sunlight reflects off the wet road ahead, creating a blinding glare. Without polarized sunglasses, this glare reduces visibility, making it difficult to see traffic signs, pedestrians, or other cars.

When you wear polarized sunglasses:

- (i) The lenses block the horizontally polarized glare from the wet road surface.
- (ii) Only vertically polarized light and non-reflective light pass through, significantly reducing glare.
- (iii) As a result, you experience clearer, sharper vision with improved contrast, enhancing safety and comfort while driving.

The detection of gravitational waves is one of the most groundbreaking achievements in modern physics, with profound scientific significance. Here's why it matters:

8.4. How will the sky appear if there had been no atmosphere?

Ans. If Earth had no atmosphere, the sky would appear completely black, even during the day. This is because the blue color of the sky is due to Rayleigh scattering, where molecules in the atmosphere scatter sunlight, with shorter blue wavelengths being scattered more than others.

Without an atmosphere:

1. **No Scattering:** There would be no particles to scatter sunlight, so no blue sky, just the blackness of space.
2. **Bright Sun:** The Sun would appear as an intensely bright, sharp disk without the soft glow or halo we usually see.
3. **Visible Stars:** Stars would be visible even during the day because there'd be no scattered sunlight to drown them out, similar to what astronauts see from space.

It would look a lot like the view from the Moon or what astronauts see from the International Space Station.

8.5. What is the significance of detecting gravitational waves?

Ans. Significance of Detecting Gravitational Waves:

1. Confirmation of Einstein's Theory of General Relativity

Gravitational waves were first predicted by Albert Einstein as part of his general theory of relativity. Detecting them directly a century later confirmed a key prediction of his theory, showing that spacetime itself can ripple due to massive cosmic events.

2. A New Way of Observing the Universe (Gravitational Wave Astronomy)

Traditional astronomy relies on electromagnetic radiation to study celestial objects. Gravitational waves, are distortions in spacetime caused by accelerating massive objects (like colliding black holes). This opens up a new "sense" for observing the universe, allowing us to "hear" cosmic events we could not "see" before.

3. Understanding Extreme Cosmic Events

Gravitational waves provide direct information about violent astrophysical processes like:

- (i) Merging black holes and neutron stars
- (ii) Supernova explosions
- (iii) Possibly even echoes from the Big Bang

These events often emit little or no light, making gravitational waves the only way to detect them.

4. Probing Black Holes and Neutron Stars

The first detected gravitational wave came from two black holes merging. This was the first direct evidence of binary black hole systems and their collisions, providing insights into the properties of black holes, such as their mass and spin.

5. Testing Fundamental Physics

Gravitational waves allow us to test:

- (i) The speed of gravity, which was found to match the speed of light.
- (ii) The nature of gravity in extreme conditions, potentially revealing physics beyond Einstein's theory.
- (iii) The equation of state of neutron stars, helping us understand matter at densities that can't be replicated on Earth.

6. Cosmology and the Expansion of the Universe

Gravitational wave events can act as "standard sirens" to measure cosmic distances, providing a new way to determine the Hubble constant, which describes the rate of expansion of the universe. This could help resolve current tensions in cosmological measurements.

7. Potential to Discover the Unknown

Just as the invention of the telescope revealed unexpected celestial objects, gravitational wave observatories might uncover phenomena we do not yet know exist, possibly shedding light on dark matter, dark energy, or even extra dimensions.

8.6. How are tidal forces formed?

Ans. Tidal forces are caused by the gravitational pull of one celestial body on another. The key factor in their formation is the difference in gravitational force experienced by different parts of an object due to the varying distance between them and the object exerting the gravitational pull.

For example, in the case of Earth and the Moon, the side of the Earth closest to the Moon experiences a stronger gravitational pull than the far side. This difference in gravitational force stretches the Earth slightly, causing a bulge of water on the side facing the Moon (a "high tide"). At the same time, the Earth itself is pulled slightly away from the water on the far side, causing another bulge (another "high tide").

The Moon's gravity creates these tidal bulges, but the Earth's own gravity causes them to align in a way that results in a cyclical rise and fall of the oceans. The Sun also exerts a tidal force, but its effect is weaker than the Moon's because it's farther away, though it still contributes to the overall tidal pattern.

COMPREHENSIVE QUESTIONS

8.1 Define the phenomenon of polarization of waves. How does polarization of electromagnetic waves occur? Also classify the polarization of waves.

Ans. See Q.1 and Q.3.

8.2 How can the plane polarized light be produced and detected? What does it prove?

Ans. See Q.4.

8.3 How can polarized light be obtained by the method of reflection? Explain.

Ans. See Q.5.

8.4 State Malus's law. Explain the intensity formula.

Ans. See Q.6.

8.5 What is a polaroid? Explain two main applications of polarization.

Ans. See Q.9.

8.6 What are gravitational waves? Describe the basic types of gravitational waves.

Ans. See Q.10 and Q.11.

8.7 What is an interferometer? Describe the basic LIGO interferometer in detail.

Ans. See Q.13, Q.14.

8.8 What is meant by optical activity? Discuss it.

Ans. See Q.7.

NUMERICAL PROBLEMS

8.1 When an unpolarized light of intensity I_0 is incident on a polarizing sheet, find the intensity of light which does not get transmitted.

Solution:

The transmitted intensity can be found by using Malus's law, which is given as:

$$I = I_0 \cos^2 \theta \quad (i)$$

where I_0 = Intensity of incident light

θ = Angle between the light's polarization direction and the transmission axis of the polarizer.

I = Intensity of transmitted light

For unpolarized light, the average value of $\cos^2 \theta$ is

$\frac{1}{2}$, therefore, the transmitted intensity I (Eq. i) becomes:

$$I = \frac{I_0}{2}$$

Now the intensity of light that is not transmitted is the difference between the incident intensity and the transmitted intensity.

$$I_{\text{not transmitted}} = I_0 - I = I_0 - \frac{I_0}{2} = \frac{2I_0 - I_0}{2} = \frac{I_0}{2}$$

So, the intensity of light that is not transmitted is $\frac{I_0}{2}$.

8.2 A polarized light beam passes through a polarizer at an angle of 45° . Find the intensity of the transmitted light if the initial intensity is 100 W m^{-2} .

Solution:

Given data:

Initial intensity $I_0 = 100 \text{ W m}^{-2}$

Angle $\theta = 45^\circ$

To Find:

Intensity of transmitted light $I = ?$

Calculations: The intensity of light passing through a polarizer can be calculated by using Malus's law:

$$I = I_0 \cos^2 \theta$$

Putting the values

$$I = 100 \text{ Wm}^{-2} \cos^2 (45^\circ)$$

$$= 100 \text{ Wm}^{-2} \times \left(\frac{1}{\sqrt{2}}\right)^2 \quad (\because \cos 45^\circ = \frac{1}{\sqrt{2}})$$

$$= 100 \text{ Wm}^{-2} \times \frac{1}{2}$$

$$\boxed{I = 50 \text{ Wm}^{-2}}$$

So, the intensity of transmitted light is 50 watt per square metre.

8.3 A light wave passes through a polarizer with its electric field aligned at 30° to the horizontal. If the amplitude of the wave is 10 units, what is the amplitude of the wave passing through the polarizer?

Solution:

Given data:

$$\text{Angle } \theta = 30^\circ$$

Amplitude of the incident wave $A_{\text{incident}} = 10$ units

To Find:

Amplitude of the wave passing through polarizer $A_{\text{transmitted}} = ?$

Calculations: The relation for the amplitude is:

$$A_{\text{transmitted}} = A_{\text{incident}} \cos \theta$$

Putting the values

$$A_{\text{transmitted}} = 10 \text{ units} \times \cos 30^\circ$$

$$= 10 \text{ units} \times \frac{\sqrt{3}}{2} \quad (\because \cos 30^\circ = \frac{\sqrt{3}}{2})$$

$$= 10 \text{ units} \times (0.866)$$

$$\boxed{A_{\text{transmitted}} = 8.66 \text{ units}}$$

So, the amplitude of the wave passing through the polarizer is approximately 8.66 units.

8.4 What angle is required between the direction of polaroid light and the axis of a polaroid filter to reduce its intensity by 85%?

Solution:

As Malus's law is

$$I = I_0 \cos^2 \theta$$

Since the intensity is reduced by 85%, so the transmitted intensity is:

$$I = 0.15 I_0$$

Using Malus's law:

$$0.15 I_0 = I_0 \cos^2 \theta$$

$$\text{or } 0.15 = \cos^2 \theta$$

Taking square root

$$\cos \theta = \sqrt{0.15}$$

$$\text{or } \cos \theta = 0.387$$

$$\text{or } \theta = \cos^{-1} (0.387)$$

$$\boxed{\theta = 67.5^\circ}$$

8.5 An unpolarized light having intensity of 15 W m^{-2} is incident on a pair of polarizers. The first polaroid filter has its transmission axis at 50° from the vertical. The second polaroid filter has its transmission axis at 20° from the vertical. Calculate the intensity of light transmitted to both filters.

Solution:

Step 1: First polarizer

An unpolarized light with intensity $I_0 = 15 \text{ Wm}^{-2}$ passes through the first polarizer, which is at 50° from the vertical. The transmitted intensity after the first polarizer is:

$$I_1 = \frac{I_0}{2}$$

Since the light is unpolarized, the first polarizer transmits half of the intensity:

$$I_1 = \frac{15 \text{ Wm}^{-2}}{2}$$

$$\boxed{I_1 = 7.5 \text{ Wm}^{-2}}$$

Step-2: Second polarized

The second polarizer has its transmission axis at 20° from the vertical. The angle between the transmission axis of the two polarizers is:

$$\theta = 50^\circ - 20^\circ = 30^\circ$$

Applying Malus's law's

$$I_2 = I_1 \cos^2 (30^\circ)$$

$$= I_1 \left(\frac{\sqrt{3}}{2}\right)^2 \quad (\because \cos 30^\circ = \frac{\sqrt{3}}{2})$$

$$I_2 = 7.5 \text{ Wm}^{-2} \times \left(\frac{\sqrt{3}}{2}\right)^2$$

$$= 7.5 \text{ Wm}^{-2} \left(\frac{3}{4}\right)$$

$$\boxed{I_2 = 5.6 \text{ Wm}^{-2}}$$

8.6 Two polarizing sheets have their polarizing directions parallel so that intensity of emitted light is maximum. Through what angle must either sheet be rotated if the intensity is to be dropped by half?

Solution:

According to Malus's law

$$I = I_0 \cos^2 \theta$$

$$\frac{I_0}{2} = I_0 \cos^2 \theta$$

$$\frac{1}{2} = \cos^2 \theta$$

$$\text{or } \cos \theta = \sqrt{\frac{1}{2}}$$

$$\text{or } \cos \theta = \frac{1}{\sqrt{2}}$$

$$\text{or } 0.707 = \cos \theta$$

$$\theta = \cos^{-1} (0.707)$$

$$\boxed{\theta = 45^\circ}$$

8.7 We wish to use a glass plate of refractive index of 1.5 in air as a polarizer. Find the polarizing angle and angle of refraction.

Solution:

Given data:

Refractive index $r = 1.5$

To Find:

(a) Polarizing angle $\theta_p = ?$

(b) Angle of refraction $r = ?$

Calculations: (a) To find the polarizing angle (also known as Brewster's angle), we use the Formula:

$$\tan (\theta_p) = \frac{n_2}{n_1}$$

where n_1 = refractive index of air i.e., 1

n_2 = refractive index of glass i.e., 1.5

Putting the values

$$\tan (\theta_p) = \frac{1.5}{1} = 1.5$$

Taking the inverse tangent

$$\theta_p = \tan^{-1} (1.5)$$

$$\boxed{\theta_p = 56.3^\circ}$$

Thus, the polarizing angle is 56.3° .

(b) The angle of refraction (r) at the polarizing angle can be calculated using Snell's law:

$$n_1 \sin (\theta_p) = n_2 \sin (r)$$

Rearranging to solve r :

$$\sin (r) = \frac{n_1 \sin (\theta_p)}{n_2}$$

Putting the values

$$\sin (r) = \frac{1 \times \sin (56.3^\circ)}{1.5} = \frac{0.83205}{1.5}$$

$$\sin (r) = 0.5547$$

$$r = \sin^{-1} (0.5547)$$

$$\boxed{r = 33.7^\circ}$$

Thus, the angle of refraction is 33.7° .

8.8 At what angle of incidence, will light reflected from water be completely polarized?

Solution:

The angle of incidence at which light is reflected from water will be completely polarized is known as Brewster's angle. It can be calculated using the Formula:

$$\tan (\theta_B) = \frac{n_2}{n_1}$$

where θ_B = Brewster's angle

n_1 = Refractive index of air ; 1

n_2 = refractive index of water ; 1.33

Putting the values

$$\tan (\theta_B) = \frac{1.33}{1}$$

$$= 1.33$$

$$\theta_B = \tan^{-1} (1.33)$$

$$\boxed{\theta_B = 53^\circ}$$

Therefore, the angle of incidence at which light will be completely polarized when reflected from water is 53° .

8.9 A beam of unpolarized light is incident on a stack of four polarizing sheets that are lined up so that the characteristic direction of each is rotated by 30° clockwise with respect to the preceding sheet. What fraction in percentage of the incident intensity be transmitted?

Sol. Using Malus's law, the intensity of light after passing through a polarizer is given by

$$I = I_0 \cos^2 \theta$$

For unpolarized light, when it first passes through the first polarizer, half of the intensity is transmitted, as the light becomes polarized in the direction of the polarizer. After that, each subsequent polarizer will transmit a fraction of the intensity based on the angle between the polarization direction of the light and the polarizer's axis.

Let us break it down step by step:

1. Initial polarizer:

The unpolarized light passes through the first polarizer. The intensity is reduced by half:

$$I_1 = \frac{1}{2} I_0$$

2. Second polarizer:

As the angle between the first and second polarizer is 30° , so the transmitted intensity will be:

$$I_2 = I_1 \cos^2 (\theta) = \frac{1}{2} I_0 \cos^2 (30^\circ)$$

$$= \frac{1}{2} I_0 \left(\frac{\sqrt{3}}{2} \right)^2 \quad \left(\because \cos 30^\circ = \frac{\sqrt{3}}{2} \right)$$

$$= \frac{1}{2} I_0 \times \frac{3}{4} = \frac{3}{8} I_0$$

3. Third polarizer:

The angle between the second and third polarizer is also 30° . The transmitted intensity will be:

$$I_3 = I_2 \cos^2 \theta = \frac{3}{8} I_0 \cos^2 (30^\circ)$$

$$= \frac{3}{8} I_0 \times \left(\frac{\sqrt{3}}{2} \right)^2$$

$$= \frac{3}{8} I_0 \times \frac{3}{4}$$

$$I_3 = \frac{9}{32} I_0$$

4. Fourth polarizer:

The angle between the third and fourth polarizer is again 30° .

Thus, the transmitted intensity will be:

$$I_4 = I_3 \cos^2 \theta = \frac{9}{32} I_0 \cos^2 \left(\frac{\sqrt{3}}{2} \right)^2$$

$$= \frac{9}{32} I_0 \times \frac{3}{4} = \frac{27}{128} I_0$$

$$I_4 = \frac{27}{128} I_0$$

Finally, the fraction of the initial intensity transmitted through all four polarizers is:

$$\frac{I_4}{I_0} = \frac{27}{128} = 0.2109$$

$$\frac{I_4}{I_0} = 21\%$$

So, the transmitted intensity is 21% of the initial intensity.

8.10 A polarizer and an analyzer have their axes aligned at 60° . What is the fraction of the initial intensity that emerges?

Solution:

The fraction of the initial intensity I that emerges when a polarizer and an analyzer have their axes aligned at an angle θ is given by Malus's law:

$$I_{\text{out}} = I_{\text{in}} \cos^2 \theta$$

Where I_{in} = Initial intensity

I_{out} = Intensity after passing through the polarizer and analyzer

θ (60°) = angle between the polarizer and analyzer axes

Putting the values

$$I_{\text{out}} = I_{\text{in}} \cos^2 (60^\circ)$$

$$= I_{\text{in}} \left(\frac{1}{2} \right)^2 \quad \left(\because \cos 60^\circ = \frac{1}{2} \right)$$

$$I_{\text{out}} = \frac{1}{4} I_{\text{in}}$$

$$\boxed{\frac{I_{\text{out}}}{I_{\text{in}}} = \frac{1}{4} = 0.25}$$

Thus, the fraction of initial intensity that emerges is 0.25.

8.11 If the gravitational waves have a wavelength of 3000 km, then find their frequency assuming it moves with the speed of light?

Solution

Using the formula:

$$f = \frac{c}{\lambda}$$

where

f = frequency

c = speed of light ($3 \times 10^8 \text{ ms}^{-1}$)

λ = wavelength ($3000 \text{ km} = 3 \times 10^6 \text{ m}$)

Putting the values

$$f = \frac{3 \times 10^8 \text{ ms}^{-1}}{3 \times 10^6 \text{ m}}$$

$$\boxed{f = 100 \text{ s}^{-1} = 100 \text{ Hz}}$$

So, the frequency of the gravitational wave is 100 Hz.