CHAPTER **8**

PHYSICAL OPTICS AND GRAVITATIONAL WAVES

STUDENT LEARNING OBJECTIVES

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

- Explain that polarization is a phenomenon associated with transverse waves.
- Define and apply Malus's law $I = I_o \cos^2\theta$ 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

Q: **Define the phenomenon of polarization of waves. How does polarization of electromagnetic waves occur? Also classify the polarization of waves.**

Ans

DEFINITION OF POLARIZATION:

Polarization is the phenomenon where the oscillations of a wave are restricted to a single plane or a specific pattern perpendicular to the direction of wave propagation. It is a property that only transverse waves exhibit.

How Polarization of Electromagnetic Waves Occurs:

Electromagnetic waves, such as light, are transverse waves consisting of oscillating electric and magnetic fields perpendicular to each other and to the direction of propagation. In unpolarized light, the electric field oscillates in all possible planes perpendicular to the direction of travel. Polarization occurs when these vibrations are limited to a single plane or a specific pattern. This can happen through:

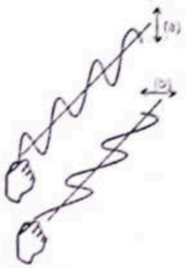


Fig. 8.1: Transverse waves on a string polarized (a) in a vertical plane, and (b) in a horizontal plane

- **Absorption (Polarizing Filters):** Materials like polaroid sheets have molecular structures that absorb electric field components vibrating in certain directions while allowing others to pass through.
- **Reflection:** When unpolarized light reflects off a non-metallic surface at a specific angle (Brewster's angle), the reflected light becomes partially or completely polarized.
- **Refraction:** Some crystals, like calcite, can split an unpolarized light beam into two refracted beams, each polarized in a different plane.
- **Scattering:** Light scattering by small particles (e.g., air molecules in the sky) can also cause polarization.

Examples of unpolarized light sources: Sunlight, regular light bulbs, fluorescent light bulbs, and light from a candle or fire are examples of unpolarized light sources.

How an Unpolarized Light can be polarized?

Unpolarized light can be made polarized in these ways:

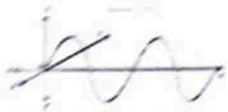
1. Passing light through a polarizing filter (like a Polaroid sheet).
2. Using a polarizing beam splitter.
3. Using certain optical crystals or materials (like calcite or quartz).

How does a polarizing filter work?

When unpolarized light goes through a polarizing filter, only the electric field vibrations that are parallel to the filter's axis can pass through. All other vibrations are blocked. The light that comes out is then polarized. (Fig. 8.3, Page 168)

In simple words, what is polarization?

Simply put, polarization is the process of changing unpolarized light into polarized light.



Basis of polarization: The direction in which the electric field vector (E) of light waves is oriented is the basis of polarization.

Plane of polarization

The plane of polarization is the flat surface that contains both the direction of the particles' vibration and the direction the wave is moving.

An unpolarized light wave: A light wave is made of electric field (E) and magnetic field (B) vectors that change periodically and are at right angle to each other. In ordinary light, these vibrations happen in all possible directions. Such light is called "unpolarized." (Fig. 8.2)

Examples of unpolarized light sources: Sunlight, regular light bulbs, fluorescent light bulbs, and light from a candle or fire are examples of unpolarized light sources.

CLASSIFICATION OF POLARIZATION OF WAVES:

The basic types of polarization for light waves are:

1. **Linear Polarization:** The electric field vector oscillates back and forth in a single plane.
2. **Circular Polarization:** The electric field vector rotates in a circle, either clockwise (right-handed) or counterclockwise (left-handed), as the wave propagates. The magnitude of the electric field remains constant.
3. **Elliptical Polarization:** The electric field vector traces an elliptical path. This is a general case that includes linear and circular polarization as special cases, where the electric field components might be unequal in magnitude or have an arbitrary phase difference.

MULTIPLE CHOICE QUESTIONS

- **Which characteristic of light is only explained by its transverse nature?**
  (a) Reflection (b) Refraction (c) Interference (d) Polarization

Answer: (d)

Explanation: Polarization involves restricting the vibration direction of a wave, a property unique to transverse waves.

- **An unpolarized light source emits light with electric field vibrations occurring:**
  (a) In a single plane only

(b) Only parallel to the direction of propagation
(c) In all possible planes perpendicular to propagation
(d) Only circularly

Answer: (c)

Explanation: Unpolarized light has electric field vibrations randomly oriented in all possible planes perpendicular to its direction of travel

- **If a wave's particles vibrate perpendicular to the wave's direction of propagation, it is a:**
(a) Longitudinal wave (b) Sound wave (c) Transverse wave (d) Stationary wave

Answer: (c)

Explanation: Transverse waves are defined by particle vibrations being perpendicular to the wave's direction of energy transfer.

- **The plane of polarization for a transverse wave is the plane containing the direction of vibration and:**
(a) The wave's amplitude (b) The wave's frequency
(c) The wave's wavelength (d) The wave's direction of propagation

Answer: (d)

Explanation: The plane of polarization is defined by the direction of vibration and the direction in which the wave is traveling.

SLO BASED SHORT QUESTIONS & ANSWERS

- **What fundamental property of light waves does polarization help us understand?**

Ans: Polarization confirms that light waves are transverse waves, meaning their oscillations are perpendicular to their direction of travel.

- **Give two common examples of unpolarized light sources.**

Ans: Sunlight and incandescent light bulbs are common examples of unpolarized light sources

- **How does the electric field vector behave in unpolarized light?**

Ans: In unpolarized light, the electric field vector vibrates randomly in all possible planes perpendicular to the direction of wave propagation

- **Can sound waves be polarized? Briefly explain why or why not.**

Ans: No, sound waves cannot be polarized because they are longitudinal waves, meaning their vibrations are parallel to the direction of wave propagation. Polarization is a property only exhibited by transverse waves.

- **What is Polarization?**

Ans: Polarization is the process that limits the electric and magnetic vibrations of light waves to a single plane. Only transverse waves, like light waves, show polarization. Sound waves, which are longitudinal, do not.

- **What is polarized light?**

Ans: If the vibrations of a light wave are limited to only one plane, the light is called "polarized."

- **What is Physical Optics in relation to polarization?**

Ans: Physical optics, when we talk about polarization, studies how light waves behave and interact with matter.

- **How do we know light is a wave?**

Ans: Interference and diffraction show that light acts like a wave.

- **What does polarization tell us about light waves?**

Ans: Polarization of light tells us that light waves are transverse waves.

- **What are transverse mechanical waves?**

Ans: In transverse mechanical waves, like waves on a stretched string, the particles of the medium move perpendicular to the direction the wave travels.

- **What is a polarized transverse mechanical wave?**

Ans: A transverse mechanical wave is "polarized" if its vibrations are limited to a specific direction (like vertical or horizontal) (Fig. 8.1, Page 167)

- **What is the plane of polarization?**

Ans: The plane of polarization is the flat surface that contains both the direction of the particles' vibration and the direction the wave is moving.

- **What is an unpolarized light wave?**

Ans: A light wave is made of electric field (E) and magnetic field (B) vectors that change periodically and are at right angle to each other. In ordinary light, these vibrations happen in all possible directions. Such light is called "unpolarized." (Fig. 8.2, Page 168)

8.2 TYPES OF POLARIZATION

Q. What are the basic types of polarization of light?

Ans

TYPES OF POLARIZATION OF LIGHT

There are three main types of polarization:

1. **Linear Polarization:**
Light is linearly polarized when its electric field vector vibrates in a single plane. (Fig. 8.4 (a)
Example: Light passing through a polarizing filter or sunglasses is an example.

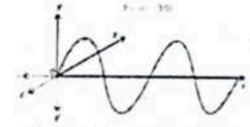


Fig. 8.4 (a): Linear polarization of light

2. **Circular Polarization:**
Light is circularly polarized when its electric field rotates in a circle, either clockwise (right-handed) or counterclockwise (left-handed). (Fig. 8.4 (b)
Example: Light reflected off a CD (Compact Disc) or DVD (Digital Versatile Disc) is an example

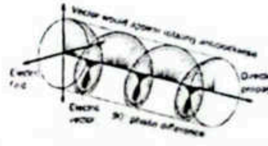


Fig. 8.4 (b): Circular polarization of light

3. **Elliptical Polarization:**
Elliptical polarization is a combination of linear and circular polarization. The electric field vector follows an elliptical path. In this type, the two parts of the electric field (Ex and Ey) are not equal, or they have a different phase angle (θ). (Fig. 8.4 (c)
Example: Light passing through a stress plate or a wave plate is an example.

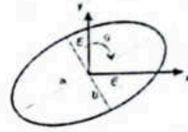


Fig. 8.4 (c): Elliptical polarization of light

MULTIPLE CHOICE QUESTIONS

- **When the electric field vector of light oscillates entirely within a single, fixed plane, the light is described as:**
(a) Circularly polarized (b) Elliptically polarized (c) Linearly polarized (d) Unpolarized

Answer: (c)

Explanation: Linear polarization occurs when the electric field vibrations are confined to a single plane

- **Light reflected off a CD or DVD is an example of which type of polarization?**
(a) Linear polarization (b) Circular polarization (c) Elliptical polarization (d) Random polarization

Answer: (b)

Explanation: Circular polarization is often observed from light reflected off such surfaces due to their microscopic groove structures.

- **Which type of polarization combines aspects of both linear and circular polarization, where the electric field vector traces an elliptical path?**
(a) Plane polarization (b) Circular polarization (c) Elliptical polarization (d) Unpolarized light

Answer: (c)

Explanation: Elliptical polarization is the most general type, where the electric field vector traces an ellipse.

- If the two perpendicular components of the electric field (Ex and Ey) are not equal or differ in phase by an arbitrary angle, the resulting polarization is:
  (a) Linear (b) Circular (c) Elliptical (d) Unpolarized

Answer: (c)

Explanation: Unequal amplitudes or an arbitrary phase difference between the components lead to elliptical polarization.

SLO BASED SHORT QUESTIONS & ANSWERS

- **Distinguish between linear and circular polarization.**

Ans: In linear polarization, the electric field vibrates in a single plane. In circular polarization, the electric field vector rotates in a circle as the wave propagates.

- **Provide an everyday example of linearly polarized light.**

Ans: Light passing through polarized sunglasses is an everyday example of linearly polarized light.

- **What condition leads to elliptical polarization of light?**

Ans: Elliptical polarization occurs when the two perpendicular components of the electric field are not equal in magnitude or differ in phase by an arbitrary angle.

- **Can light be "partially polarized" as a type of polarization? Explain.**

Ans: "Partially polarized" light is not a fundamental type like linear or circular, but rather a state where some light is polarized and some is not. It means the electric field vibrations have a preferred orientation but are not entirely confined to one plane or a regular path.

8.3 PRODUCTION AND DETECTION OF PLANE POLARIZED LIGHT

Q. How is plane polarized light produced and detected?

Ans

Light from an ordinary incandescent bulb is unpolarized because its electrical vibrations are random.

If unpolarized light shines on a polaroid sheet (called a polarizer), the light that passes through will be plane polarized.

If we place a second polaroid sheet (called an analyzer) with its axis parallel to the first polarizer's axis (Fig. 8.5-a), the light will pass through the second polaroid.

If we slowly turn the analyzer around the light beam, the light coming out of the second polaroid will get dimmer and dimmer. It will disappear completely when the axes are exactly perpendicular to each other (Fig. 8.5-b). The light will then reappear as you keep rotating it, and it will be brightest again when the axes are parallel.

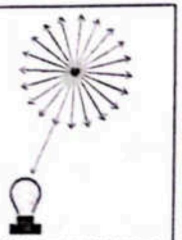


Fig. 8.2: An unpolarized light, due to incandescent bulb, has vibrations in all planes.

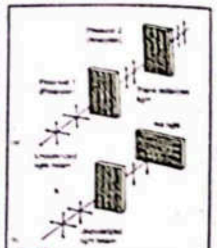


Fig. 8.3 Experimental arrangement to show that light waves are transverse. The lines with arrows indicate electric vibrations of light waves.

Result:

This experiment proves that light waves are transverse waves. If light waves were longitudinal, they would not disappear even if the two polaroids were perpendicular.

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

Ans

PRODUCTION OF PLANE POLARIZED LIGHT:

Plane polarized light can be produced from unpolarized light by:

1. **Using Polarizing Filters (Polaroids):** The most common method. When unpolarized light passes through a polaroid sheet (called a polarizer), the filter's molecular alignment allows only electric field vibrations parallel to its transmission axis to pass through, resulting in plane polarized light.
2. **Reflection:** When unpolarized light strikes a transparent, non-metallic surface (like glass or water) at a specific angle (Brewster's angle), the reflected light becomes largely plane polarized.
3. **Refraction:** Certain optically anisotropic crystals (like calcite) can produce two refracted rays from unpolarized light, each plane polarized in mutually perpendicular planes.
4. **Scattering:** Scattering of light by particles (e.g., Rayleigh scattering in the atmosphere) can also produce partially plane polarized light.

Detection of Plane Polarized Light:

Plane polarized light is detected using a second polarizing filter, called an analyzer.

- First, unpolarized light is passed through a polarizer to create plane polarized light.
- Then, this plane polarized light is passed through an analyzer.
- If the analyzer's transmission axis is parallel to the plane of polarization of the incident light, maximum intensity is transmitted.
- If the analyzer is rotated, the intensity of the transmitted light decreases according to Malus's Law ($I = I_0 \cos^2\theta$).
- When the analyzer's axis is perpendicular to the plane of polarization (crossed polaroids, $\theta = 90°$), the light is completely extinguished (zero intensity).
- As the analyzer is rotated further, light reappears and reaches maximum intensity again when the axes are parallel ($\theta = 0°$ or $180°$).

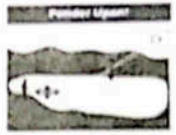
Conclusion: (What does it prove?)

This production and detection experiment, especially the complete extinction of light when the polarizer and analyzer axes are perpendicular, definitively proves that light waves are transverse waves. If light waves were longitudinal (vibrating parallel to the direction of propagation), they would always be able to pass through the second filter, regardless of its orientation, and complete extinction would not occur.

Ponder Upon! (Page 170)

- **Why is light reflected from a smooth surface of water partially polarized parallel to the surface?**

Ans: Light reflected from a smooth surface of water is partially polarized parallel to the surface because the components of the electric field parallel to the surface are reflected more strongly than components perpendicular to the surface, especially at certain angles of incidence.



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

MULTIPLE CHOICE QUESTIONS

- **What is the primary function of a polarizer in an optical setup?**
  (a) To reflect light (b) To refract light
  (c) To convert unpolarized light into plane-polarized light
  (d) To increase light intensity

Answer: (c)

Explanation: A polarizer selectively transmits electric field vibrations in one direction, thereby polarizing unpolarized light.

- **If an unpolarized light passes through two polaroids that are "crossed" (axes perpendicular), the light emerging from the second polaroid will be:**
  (a) Maximum intensity (b) Half intensity (c) Zero intensity (d) Circularly polarized

Answer: (c)

Explanation: When polaroids are crossed, the analyzer blocks all the polarized light transmitted by the first polarizer, resulting in zero intensity.

- An analyzer is essentially:
  (a) A mirror (b) A lens (c) A second polarizer (d) A prism

Answer: (c)

Explanation: An analyzer is functionally a polarizer used to detect or measure the properties of already polarized light.

- The experiment involving two rotating polaroids (polarizer and analyzer) conclusively demonstrates that light waves are:
  (a) Longitudinal (b) Mechanical (c) Transverse (d) Stationary

Answer: (c)

Explanation: The ability to completely block light by rotating the second polaroid proves that light vibrations are transverse and can be aligned or blocked.

SLO BASED SHORT QUESTIONS & ANSWERS

- **How can an ordinary incandescent bulb's light be described in terms of polarization?**

Ans: Light from an ordinary incandescent bulb is described as unpolarized because its electrical vibrations are randomly oriented in all possible planes.

- **When using a polarizer and an analyzer, what observation indicates that the incident light on the analyzer is plane polarized?**

Ans: If the intensity of light passing through the analyzer varies from maximum to minimum (or zero) as the analyzer is rotated, it indicates the light incident on it is plane polarized.

- **Name one type of optical crystal mentioned that can confine light vibrations to one plane.**

Ans: Tourmaline or calcite crystals are types of optical crystals that can confine light vibrations to one plane.

- **Why would light not disappear if it were longitudinal waves passing through two mutually perpendicular polaroids?**

Ans: If light were longitudinal, its vibrations would always be parallel to its direction of propagation, meaning the polaroids would not be able to block them, and light would pass through regardless of their orientation.

8.4 POLARIZATION OF LIGHT BY THE METHOD OF REFLECTION

Q. How can polarized light be obtained by reflection?

Ans

In 1808, Malus found that polarized light can be produced when ordinary light reflects off a flat glass surface. If you look at the reflected light through a polaroid and slowly rotate it, the light will almost disappear at a certain angle.

For glass, the best angle of incidence is about 57°. At this angle, the reflected light becomes plane polarized. (Fig. 8.6, Page 170) This shows that light reflected by glass is mostly plane polarized. Light reflected from a table surface also gets darker when viewed through a rotated polaroid, meaning it is partially plane polarized.

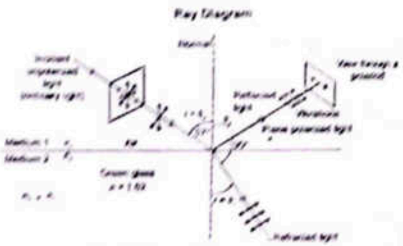


Fig 8.6: Plane polarization by reflection

BREWSTER'S LAW

The specific angle at which light hits a transparent material, causing the reflected light to be almost plane polarized, is called the polarizing angle. It is also known as the Brewster angle, denoted as θ_p or θ_B.

What happens at the polarizing angle according to Brewster's Law?

When unpolarized light hits a surface, and the reflected light is almost plane polarized, the reflected and refracted light beams are at a 90° angle to each other at the polarizing angle.

So, $\theta_p+\theta_r=90°$, which means $\theta_r=90°-\theta_p$

What is the formula for Brewster's Law?

Using Snell's Law ($n_1\sin\theta_p=n_2\sin\theta_r$), and substituting $\theta_r=90°-\theta_p$, we get:

$$n_1\sin\theta_p=n_2\sin(90°-\theta_p)$$
$$n_1\sin\theta_p=n_2\cos\theta_p$$
$$\sin\theta_p/\cos\theta_p=n_2/n_1$$
$$\tan\theta_p=n_2/n_1 \quad \text{(Equation 8.1)}$$

Here, n_1 is the refractive index of medium 1, and n_2 is the refractive index of medium 2. This equation is known as Brewster's Law.

What is Brewster's Law if medium 1 is air?

If medium 1 is air ($n_1=1$), the equation becomes $\tan\theta_p=n$, where n is the refractive index of medium 2.

So, Brewster showed that the tangent of the polarizing angle is equal to the refractive index of the medium. The angle θ_p where the reflected and refracted rays are 90° apart is also called the Brewster angle θ_B. So, $\tan\theta_B=n$

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

Ans

Polarized light can be obtained by the method of reflection when unpolarized light strikes a boundary between two transparent dielectric media (e.g., air and glass).

Explanation:

When ordinary (unpolarized) light is incident on a surface, its electric field vectors vibrate in all possible directions perpendicular to its propagation. When this light encounters a surface, the component of the electric field that is parallel to the plane of incidence (the plane containing the incident ray, reflected ray, and the normal to the surface) is refracted and reflected differently than the component perpendicular to the plane of incidence.

At a specific angle of incidence, known as **Brewster's Angle** (θ_p or θ_B), something unique happens:

- The component of the electric field parallel to the plane of incidence is entirely refracted into the second medium.
- The component of the electric field perpendicular to the plane of incidence is predominantly reflected.
- At Brewster's angle, the reflected ray and the refracted ray are exactly 90° apart.

According to Brewster's Law, $\tan\theta_p=n_2/n_1$, where n_1 and n_2 are the refractive indices of the first and second media, respectively. If the first medium is air ($n_1=1$), then $\tan\theta_p=n_2$.

Therefore, when unpolarized light is incident at Brewster's angle, the reflected light becomes almost completely plane polarized, with its electric field vibrations perpendicular to the plane of incidence (i.e., parallel to the surface). The refracted light, on the other hand, is partially polarized. This method is commonly used to produce polarized light from ordinary light sources.

INTERESTING INFORMATION (PAGE 171)

Q: **What is Malus's law used to study in biological systems?**

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

MULTIPLE CHOICE QUESTIONS

- At the polarizing angle, what is the angle between the reflected light and the refracted light?
  (a) 0° (b) 45° (c) 90° (d) 180°

Answer: (c)

Explanation: Brewster's law states that at the polarizing angle, the reflected and refracted beams are exactly perpendicular (90°) to each other.

- **Brewster's Law states that the tangent of the polarizing angle is equal to the medium's:**
  (a) Angle of incidence (b) Angle of refraction (c) Refractive index (d) Critical angle

Answer: (c)

Explanation: For light incident from air, $\tan\theta p = n$, where n is the refractive index of the medium.

- **Light reflected from the surface of a table is often described as:**
  (a) Completely unpolarized (b) Completely plane polarized
  (c) Partially plane polarized (d) Circularly polarized

Answer: (c)

Explanation: Most reflections from non-metallic surfaces result in partially polarized light, where some components are more dominant than others.

- **If the refractive index of a medium is 1, what is its polarizing angle?**
  (a) 0° (b) 45°
  (c) 90° (d) It cannot have a polarizing angle

Answer: (b)

Explanation: If n=1, then $\tan\theta_p = 1$, which means $\theta_p = 45°$, since $\tan 45° = 1$

SLO BASED SHORT QUESTIONS & ANSWERS

- **Define the term "polarizing angle."**

Ans: The polarizing angle (or Brewster's angle) is the specific angle of incidence on a transparent medium at which the reflected light becomes almost completely plane polarized.

- **What happens to the reflected light at the polarizing angle when unpolarized light is incident on a transparent surface?**

Ans: At the polarizing angle, the reflected light becomes almost completely plane polarized, with its electric field vibrations parallel to the surface.

- **According to Brewster's law, how is the polarizing angle related to the refractive indices of the two media?**

Ans: Brewster's law states that the tangent of the polarizing angle ($\tan\theta p$) is equal to the ratio of the refractive index of the second medium (n2) to the first medium (n1), i.e., $\tan\theta p = n1n2$

- **Why does light reflected from a smooth road surface often cause glare?**

Ans: Light reflected from smooth surfaces like roads becomes predominantly horizontally polarized. This highly aligned reflected light is perceived as glare because it can be very intense and interfere with vision

8.5 MALUS'S LAW

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

Ans

Malus's law state?

Malus's law states that the intensity (I) of plane polarized light after passing through an analyzer is directly proportional to the square of the cosine of the angle (θ) between the transmission axis of the analyzer and the polarizer.

Formula for Malus's law

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

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

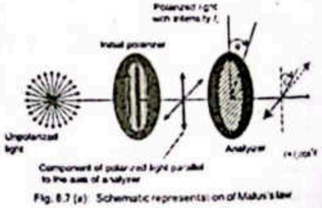


Fig. 8.7 (a) Schematic representation of Malus's law

Where I_0 is the intensity of the incident polarized light. (Fig. 8.7 (a), Page 172)Actually, Malus's law gives a mathematical relation between

the intensity of the light (incident light) on the first polaroid (i.e. polarizer) and the intensity of light obtained after passing it through the second polaroid (i.e., analyzer).

Role of an Analyzer

An analyzer is also a polarizer that is placed after the first polarizer. Rotating the analyzer changes the intensity of the polarized light. It is used to further reduce and adjust the light's intensity by changing its angle relative to the polarizer.

Polaroids

Certain transparent crystalline materials, like tourmaline and calcite crystals, can restrict light wave vibrations to a single plane. These materials are called polaroids because their crystal structure is highly directional.

Light Polarization

Light can also be polarized by natural processes like reflection, refraction, and scattering.

How does changing the angle between polaroids affect light intensity?

If a polaroid is rotated in front of a polarized light ray, the intensity of the light that passes through changes. This change is due to the angle between the first polarizer and the axis of the second polarizer.

MALUS'S LAW DERIVATION FROM AMPLITUDE

When polarized light with amplitude A_0 hits the analyzer at an angle θ, its amplitude is split into two parts:

1. **Component parallel to the analyzer's axis:** This component is $A_0 \cos\theta$, where A_0 is the amplitude of the incident polarized light. This component is transmitted through the analyzer.
2. **Component perpendicular to the analyzer's axis:** This component is $A_0 \sin\theta$. This component is blocked or absorbed by the analyzer.
   So, the amplitude (A) of the transmitted light is:
   $A = A_0 \cos\theta$(Equation 8.2)

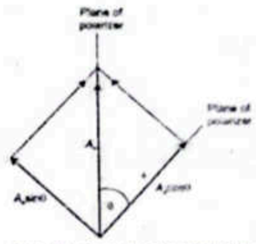


Fig. 8.7(b) Resolution of amplitude into components of plane polarization light

Since intensity (I) is proportional to the square of the amplitude (A^2), we can write:

$I = kA^2$ (where k=1, so $I = A^2$)

Substituting $A = A_0 \cos\theta$:

$I = (A_0 \cos\theta)2$

$I = A_0^2 \cos^2\theta$

Since $I_0 = A_0^2$ (initial intensity), we get:

$I = I_0 \cos^2\theta$

Extreme Conditions For Malus's Law?

1. If θ=0°: Then $I = I_0\cos^2(0°) = I_0 \times 1^2 = I_0$. This means the intensity of light transmitted through the analyzer is equal to the initial light intensity that passed through the polarizer.
2. If θ=90°: Then $I = I_0 \cos^2(90°) = I_0 \times 0^2 = 0$. This means the light is completely blocked, and no light passes through the analyzer.

Q. What is meant by optical activity? Discuss it.

Ans

OPTICAL ACTIVITY

Optical activity is the ability of a substance to rotate the plane of polarization of light as it passes through it. This rotation is detected using a polarizer or analyzer. (Fig. 8.8)

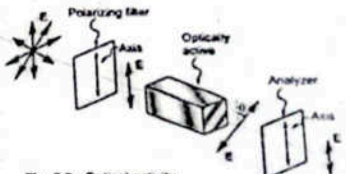


Fig. 8.8: Optical activity

What types of substances show optical activity?

Many crystals and solutions can rotate the plane of polarization of light. These substances are called optically active. Examples include quartz crystals, cinnabar (H_gS), sugar water, insulin, and collagen.

Factors Affect the Amount and Direction of Rotation in Optically Active Substances

The amount and direction of rotation depend on:

(i) The type of substance

(ii) The concentration of the substance (how much of it is in a mixture or solution)

(iii) The distance the light travels through the substance

(iv) The wavelength of the light

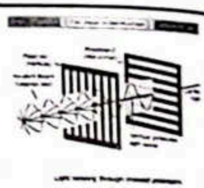
Reason of Optical Activity

Optical activity happens because the molecules in the substance have an asymmetric shape, like a helix. A few millimeters of such crystals can rotate the plane of polarization by many degrees. Some organic substances, like sugar and tartaric acid, show optical rotation when in a solution. This property can be used to find the concentration of these substances in solutions.

For your information (Page 173)

Question: What happens when light passes through crossed polarizers?

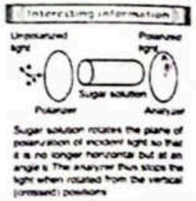
Answer: When light passes through two polarizers that are "crossed" (their axes are perpendicular), very little to no light passes through.



Interesting Information (Page 173)

Question: How does a sugar solution rotate the plane of polarization, and how does an analyzer detect this?

Answer: A sugar solution rotates the plane of polarization of incident light. The analyzer then stops the light when rotated from its initial vertical (crossed) position, indicating the rotation



Do you know? (Page 174)

Question: What happens when you look through two polarizers that are "crossed"?

Answer: When two polarizers are "crossed" (their transmission axes are perpendicular), very little light passes through them.

Tidbit (Page 174)

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

Answer: When unpolarized light passes through a foggy atmosphere, the scattered light will be partially polarized. This is because light scattering by small particles (like water droplets in fog) can lead to polarization, especially when viewed at 90° to the incident light.

Tidbit

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

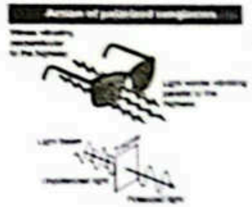
IMPORTANCE OF POLARIZATION

Polarization of light is very important in various fields:

1. **Optics and Photonics:** Polarization is crucial for things like polarized sunglasses, LCD (Liquid Crystal Display) screens, and optical communication systems.
2. **Imagine and Microscopy:** Polarization improves image quality by reducing glare (unwanted light that interferes with vision) and making contrast better, especially in microscopy and medical imaging.
3. **Medical Applications:** Polarization is used in diagnosing cancer, imaging tissues, and laser surgery because it can tell the difference between various tissue types.
4. **Astronomy:** Polarization helps scientists study cosmic events, such as the polarization of light from distant stars or the cosmic microwave background radiation.
5. **Miscellaneous fields:** Polarization is also important in areas like optics and photonics, imaging and microscopy, biology and chemistry, and communication systems.

TWO MAIN APPLICATIONS OF POLARIZATION

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



1. **Sky Photography**

Cameras used to photograph clouds are fitted with a polaroid. The polaroid polarizes the light coming from the sky.

In sky photography, polarizers reduce glare and haze caused by light scattering from small particles in the atmosphere. They also improve contrast by blocking too much bright white light while letting other colors pass through, which creates a brighter, more detailed image and improves overall image quality.

2. **Stress Analysis of Materials**

In materials science, polarizers are used to analyze stress and strain in materials like plastics, metals, and glass.

When a material is stressed, its molecular structure changes, which affects how it interacts with light. This creates interference patterns or fringes, giving information about the material. By shining polarized light through transparent material and analyzing changes in the light's polarization, researchers can:

- Find the material's stress patterns.
- Spot possible weaknesses or defects.
- Analyze the material's optical properties.
- Understand how the material will behave under different conditions.

This method is called "photoelasticity" and is widely used in engineering, materials science, and quality control.

In both these cases, polarizers are essential for controlling light to achieve specific goals, whether it's making images better or analyzing material properties.

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

Ans

POLAROID

A polaroid (or polarizing filter) is a material or sheet that polarizes light. It allows light waves vibrating in a specific direction (its transmission axis) to pass through while absorbing or blocking light waves vibrating in other directions. Polaroids are typically made of stretched polymer sheets containing aligned long-chain molecules or microscopic crystals.

Two Main Applications of Polarization:

1. **Sky Photography:**
   - **How it works:** In sky photography, a polarizing filter is attached to the camera lens. Sunlight scattered by atmospheric particles (like air molecules) becomes partially polarized. Glare and haze from the sky are often due to this scattered, partially polarized light.

- **Benefit:** The polaroid allows photographers to selectively block or reduce this scattered, polarized light. By rotating the filter, they can control the amount of glare and haze, making the blue sky appear deeper and clouds stand out more vividly. It enhances contrast and color saturation by removing unwanted light.

2. **Stress Analysis of Materials (Photoelasticity):**
   - **How it works:** This application involves transparent materials (like plastics or glass) that become optically active when stressed. When polarized light is passed through a stressed material, the stress patterns cause the light's polarization to change. The light then passes through a second polaroid (an analyzer).
   - **Benefit:** The changes in polarization create visible interference patterns (like colored fringes) when viewed through the analyzer. These patterns reveal the distribution of stress and strain within the material. Engineers and scientists use this technique to identify potential weaknesses, defects, or areas of high stress in components, ensuring their structural integrity and safety. It's a non-destructive way to analyze material behavior.

8.6 GRAVITATIONAL WAVES (GWS)

A gravitational wave is a stretching and compressing of space-time. We can observe it by measuring changes in length between two objects.

Gravitational waves (GWs) in simple terms

Gravitational waves (GWs) are like "ripples in the fabric of space-time." They are created by powerful cosmic events, such as colliding black holes or neutron stars. They travel at the speed of light and carry information about their source.

Albert Einstein (1879-1955)
A German born Theoretical Physicist
One of the World's renowned scientists

Simple example to understand GWs

Imagine throwing a stone into a pond. The stone makes ripples on the water's surface (which is like space-time). These ripples travel outward, carrying information about the stone (the cosmic event). These ripples can be detected on the shore (by gravitational wave observatories), telling us about the stone's presence and properties.

Prediction and Detection

Gravitational waves were predicted by Albert Einstein in 1916 as part of his theory of general relativity.

Gravitational waves were first detected in 2015 and announced in 2016. This was the first observation of its kind, specifically from two colliding neutron stars. In this type of event, the frequency and amplitude of the GWs gradually increase.

What is a Binary System (BS) in the context of gravitational waves?

A Binary System (BS) is a system of two compact objects, like black holes, neutron stars, or white dwarfs, that orbit each other and release gravitational waves.

BS Model

Four Basic Types of GWs

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

1. **Continuous GWs**

   Continuous GWs are produced when a single massive object, like a neutron star, spins at a constant rate. They have a constant frequency and amplitude. White dwarf binary systems also produce continuous GWs.

2. **Compact Binary Inspirational GWs**

   These are produced when a binary system, such as binary neutron stars, binary black holes, or a neutron star and a black hole, orbit each other.

3. **Burst GWs**

   Burst GWs are created by violent events like supernovae, gamma-ray bursts, or cosmic strings.

4. **Stochastic GWs**

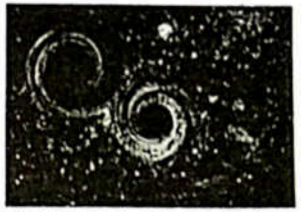
   Stochastic GWs are faint, random signals of gravitational waves. They are made by the combination of many weak gravitational wave sources, like distant binary systems. These GWs are the hardest to detect.

Accelerating Objects Produce Gravitational Waves

Every physical object that accelerates produces gravitational waves, including vehicles and airplanes. However, the masses and acceleration of objects on Earth are too small to create gravitational waves strong enough to be detected by our instruments.

How do binary systems relate to GW detection?

As binary systems orbit each other, they emit gravitational waves. These waves can be detected by observatories like LIGO (Laser Interferometer Gravitational-wave Observatory) in the USA and Virgo in Italy. These waves carry information about the system's mass, spin, and how they merge, giving us insights into these extreme cosmic objects. They travel at the speed of light.



Tidal forces carry the mathematical signature of gravitational waves

How do gravitational waves propagate?

As masses orbit and accelerate, their gravitational intensity changes, creating waves that spread outward in all directions. These waves are not held by the binary system's gravity; instead, they travel freely through space-time at the speed of light. The waves become weaker as they move farther from their source.

What is the significance of binary system mergers?

Binary systems are important sources of gravitational waves, and their mergers (when two massive objects collide and combine into one larger object) are among the most intense cosmic events.

What do the characteristics of GWs depend on?

The features of gravitational waves depend on the binary system's properties, such as:

- Masses of the objects
- Orbital period and frequency
- Eccentricity of the orbit: Eccentricity (e) measures how much an object's orbit differs from a perfect circle.
  - $e=0$: Circular orbit
  - $0<e<1$: Elliptical orbit
  - $e=1$: Parabolic trajectory
  - $e>1$: Hyperbolic trajectory

Dr. Nergis Mavalwala (Page 177)

Information: Dr. Nergis Mavalwala is a Pakistani-American astrophysicist at MIT, well-known for her work on gravitational waves.

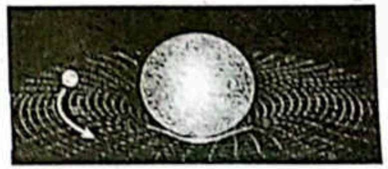
Dr. Nergis Mavalwala is a Pakistani-American Astrophysicists at MIT known for her work on gravitational waves

Space-time Distortion / Tidal Forces

Gravitational waves passing through a body with mass can make the body periodically stretch and compress. This effect is known as "space-time distortion" or "tidal forces."

How do tidal forces arise from gravitational waves?

As a gravitational wave moves through a body, it causes the space-time around the body to vibrate. This leads to the body periodically stretching and compressing in the direction perpendicular to the wave's movement. This is similar to how the Moon and Sun's gravitational pull causes tides on Earth.



Spacetime curve shown by two satellites

What factors influence the amount of stretching and compressing?

The amount of stretching and compressing depends on the strength of the gravitational wave and the mass and size of the body. This effect is an important prediction of Einstein's general theory of relativity.

Do gravitational waves from far-off events affect Earth?

Gravitational waves generated by distant cosmic events, like the merger of two black holes or neutron stars, do pass through the Earth. However, their amplitude is extremely small, typically around 10^{-21} to 10^{-22} meters. This means the distortion caused by the gravitational wave is incredibly tiny and needs extremely sensitive instruments to detect.

Spacetime curve of an artificial and a natural satellite

What is the significance of detecting these tiny gravitational waves?

Despite their small amplitude, gravitational waves provide a unique way to study the universe. They allow us to study strong-field gravity, test general relativity, and explore the universe in ways that were previously impossible.

8.7 INTERFEROMETER

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

Ans

INTERFEROMETER?

An interferometer is an optical tool used to detect gravitational waves. It is a very sensitive device that uses the interference of LASER (Light Amplification by Stimulated Emission of Radiation) beams. The basic LIGO interferometer is shown in Fig. 8.9 (Page 179)

How do interferometers detect gravitational waves?

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

Differences Between LIGO And Conventional Interferometers?

(a) LIGO is 1000 times larger than a conventional device.

(b) LIGO uses LASER light, while conventional interferometers use normal light sources.

Basic Components of GW Interferometer

The basic components are:

1. **Laser:** Produces a steady and high-intensity beam of light.
2. **Power recycling mirror:** Continuously reflects LASER light that has already traveled through the instrument back into the interferometer, thus "recycling" it.
3. **Beam splitter:** Divides the LASER beam into two perpendicular beams.
4. **Mirrors:** Reflect the beams, creating two perpendicular arms.
5. **Fabry-Perot cavity:** Consists of two mirrors facing each other. Its purpose is to increase the path length of the light.
6. **Photodetectors:** Measure the returning beams and detect tiny phase shifts.
7. **Arm cavities:** Enhance the LASER light, increasing sensitivity (Fig. 8.9, Page 179)

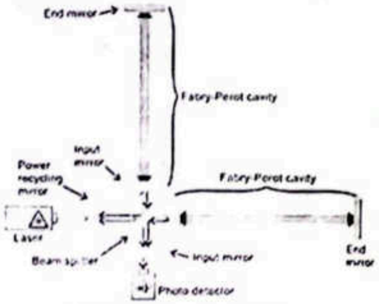


Fig. 8.9: Basic LIGO Interferometer

Working of Interferometer

A laser beam is split into two perpendicular beams. Each beam travels 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 change in the distance between the mirrors. This results in a "phase shift" between the two beams. When the beams recombine, they create an interference pattern, which is measured by a photodetector. The small phase shift caused by the gravitational wave changes the interference pattern, allowing the detector to sense the wave's presence.

Gravitational Waves First Observed By LIGO (The Laser Interferometer Gravitational-Wave Observatory)

On September 14, 2015, the universe's gravitational waves were observed for the very first time by LIGO. These waves, predicted by Albert Einstein 100 years ago, came from a collision between two black holes. It took 1.3 billion years for these waves to reach the LIGO detector in the USA.

Nobel Prize For the Observation of GWS (Gravitational Waves)

Rainer Weiss, Barry C. Barish, and Kip S. Thorne received the Nobel Prize in 2017 for their work on observing gravitational waves. It's noteworthy that Nergis Mavalwala, a professor at MIT, is from Pakistan and was part of the team.

Virgo Detection

Virgo is another facility for measuring gravitational waves, similar to LIGO. It operates under the European Gravitational Observatory (EGO) near Pisa, Italy. Virgo is also an interferometer, but its two arms are 3 km long, whereas LIGO has 4 km arms.

The Virgo Observatory is named after the Virgo constellation, which is visible in the night sky during March, April, and May. The Virgo cluster is a group of about 1,500 galaxies, about 50 MLYs (Million Light Years) away.

Light Year (LY)?

One Light Year (LY) is the distance light travels in one year. Its approximate value is 9.5 billion km.

Virgo first detect gravitational waves?

Virgo has been involved in detecting gravitational wave events, with its first detection in 2017.

MULTIPLE CHOICE QUESTIONS

- **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
  Correct Answer: (b)
- **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
  Correct Answer: (a)
- **The intensity of light when it passes through a polarizer:**
  (a) increases (b) decreases (c) remains the same (d) becomes zero
  Correct Answer: (b)
- **The angle between the light wave and the analyzer is called:**
  (a) polarization angle (b) refraction angle (c) reflection angle (d) azimuth angle

Correct Answer: (a) (Note: The angle between the polarizer and analyzer axis is usually denoted by θ in Malus's law, and this θ is often referred to as the polarization angle in this context, although "azimuth angle" can also refer to rotation.)

- **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

Correct Answer: (b) (An analyzer's primary role is to determine the state of polarization and measure the intensity of the polarized light.)

- **The mathematical representation of Malus's law is:**
(a) $I=I_o\cos^2\theta$ (b) $I=I_o\sin^2\theta$ (c) $I=I_o\tan^2\theta$ (d) $I=I_o\cot^2\theta$

Correct Answer: (a)

- **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

Correct Answer: (b) (As θ increases from 0° to 90°, $\cos^2\theta$ decreases, so I decreases.)

- **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°

Correct Answer: (b) (Maximum intensity occurs when $\theta=0°$, meaning parallel axes.)

- **The unwanted light that interferes with vision is termed as:**
(a) haze (b) glare (c) contrast (d) flare

Correct Answer: (b)

- **Who predicted the existence of gravitational waves?**
(a) Galileo Galilei (b) Albert Einstein (c) Isaac Newton (d) Leonardo da Vinci

Correct Answer: (b)

- **What are gravitational waves?**
(a) Electromagnetic waves (c) Ocean waves
(d) Ripples in the fabric of spacetime (b) Mechanical Waves

Correct Answer: (d)

- **Which is the primary method used to detect gravitational waves?**
(a) Optical telescopes (c) LASER interferometry (b) Radio telescopes (d) Gravitational lensing

Correct Answer: (c)

- **Which of the following is a primary source of gravitational waves?**
(a) Binary black hole merger (c) Earthquake (b) Solar flares (d) Solar wind

Correct Answer: (a)

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TEXT BOOK EXERCISE WITH SOLUTION

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

Correct Answer: (b)

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

Correct Answer: (a)

8.3 The intensity of light when it passes through a polarizer:
(a) increases (b) decreases
(c) remains the same (d) becomes zero

Correct Answer: (b)

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

Correct Answer: (a) (Note: The angle between the polarizer and analyzer axis is usually denoted by θ in Malus's law, and this θ is often referred to as the polarization angle in this context, although "azimuth angle" can also refer to rotation.)

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

Correct Answer: (b) (An analyzer's primary role is to determine the state of polarization and measure the intensity of the polarized light.)

8.6 The mathematical representation of Malus's law is:
(a) $I=I_o\cos^2\theta$ (b) $I=I_o\sin^2\theta$
(c) $I=I_o\tan^2\theta$ (d) $I=I_o\cot^2\theta$

Correct Answer: (a)

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

Correct Answer: (b) (As θ increases from 0° to 90°, $\cos^2\theta$ decreases, so I decreases.)

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°

Correct Answer: (b) (Maximum intensity occurs when $\theta=0°$, meaning parallel axes.)

8.9 The unwanted light that interferes with vision is termed as:
(a) haze (b) glare
(c) contrast (d) flare

Correct Answer: (b)

8.10 Who predicted the existence of gravitational waves?
(a) Galileo Galilei (b) Albert Einstein
(c) Isaac Newton
(d) Leonardo da Vinci

Correct Answer: (b)

8.11 What are gravitational waves?
(a) Electromagnetic waves
(b) Mechanical Waves
(c) Ocean waves
(d) Ripples in the fabric of space time

Correct Answer: (d)

8.12 Which is the primary method used to detect gravitational waves?
(a) Optical telescopes
(b) Radio telescopes
(c) LASER interferometry
(d) Gravitational lensing

Correct Answer: (c)

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

Correct Answer: (a)

SHORT ANSWER QUESTIONS

8.1 Why are polaroid sunglasses better than ordinary sunglasses?

Ans: Polaroid sunglasses are better because they reduce glare, which is unwanted light reflected from surfaces like water or roads. They do this by blocking horizontally polarized light, allowing you to see more clearly and comfortably. Ordinary sunglasses only reduce the overall brightness.

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

Ans: Yes, light from the sky is partially polarized. This happens due to the scattering of sunlight by air molecules. The degree of polarization depends on the angle relative to the sun. Light scattered at 90° to the incident sunlight is most strongly polarized.

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

Ans: Malus's law is used in designing polarized sunglasses and LCD screens. In sunglasses, it helps control the amount of light that passes through, reducing glare. In LCDs, it's used to control the light passing through pixels to create images.

8.4 What are the applications of Brewster's angle?

Ans: Brewster's angle is used in:

- Designing polarizing filters and devices that block reflected glare, like those in sunglasses.
- Creating "Brewster windows" in lasers to minimize reflection losses for a specific polarization.
- In optics, to understand how light reflects and refracts at interfaces between different materials.

8.5 What is the space-time curvature?

Ans: Space-time curvature is the idea from Einstein's general theory of relativity that massive objects (like planets or stars) warp or "dent" the fabric of space-time around them. Due to this warping we experience gravity.

8.6 How are tidal forces formed?

Ans: Tidal forces are formed when a gravitational field is not uniform across a body. For example, in the context of gravitational waves, as a GW passes through a body, it causes different parts of the body to experience slightly different gravitational pulls, leading to periodic stretching and compressing. On Earth, the Moon's gravity pulls on the side of Earth closer to it more strongly than on the far side, creating ocean tides.

CONSTRUCTED RESPONSE QUESTIONS

8.1 Write down some applications of plane polarized light.

Ans: Applications of plane polarized light include:

- **Polarized Sunglasses:** To reduce glare from reflective surfaces.
- **LCD Screens:** To control light transmission for displaying images.
- **Stress Analysis (Photoelasticity):** To visualize stress patterns in transparent materials like plastics.
- **Optical Instruments:** In microscopes and scientific equipment for specific light manipulation.
- **Sky Photography:** To enhance contrast and reduce atmospheric haze.
- **Medical Imaging:** In certain techniques to distinguish tissue types.

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

Ans: Yes, it is possible to use a polarizer as an analyzer. An analyzer is essentially a second polarizer placed after a primary polarizer to examine the properties of the light that has already been polarized.

Examples:

1. **Detecting Plane Polarized Light:** If you have an unknown light source, you can use a polarizer as an analyzer. If rotating it causes the light intensity to vary from bright to dark, it indicates the light is plane polarized.
2. **Determining Concentration of Optically Active Substances:** In a lab, a polarizer can act as an analyzer to measure the rotation of polarized light caused by a sugar solution. The amount of rotation helps determine the sugar's concentration.

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

How Malus's Law is used in Polarized Sunglasses:

Ans: Polarized sunglasses are designed using the principles of polarization and Malus's law. Glare from horizontal surfaces (like water, snow, or roads) is mostly horizontally polarized. Polarized sunglasses have a special filter (a polarizer) with its transmission axis oriented vertically. This vertical orientation means they block a large portion of the horizontally oscillating light waves that cause glare, while allowing vertically oscillating light waves (which carry useful visual information) to pass through.

How they reduce glare: When unpolarized light hits a reflective surface at a certain angle (near Brewster's angle), the reflected light becomes largely horizontally polarized. Polarized sunglasses act as an analyzer that is "crossed" or nearly crossed with this horizontally polarized glare. According to Malus's law ($I=I_0\cos^2\theta$), if the angle θ between the horizontally polarized glare and the vertically aligned transmission axis of the sunglasses is 90°, then $\cos^2(90°)=0$, and the intensity I becomes zero. In reality, it's rarely a perfect 90°, so the glare is significantly reduced rather than completely eliminated.

Example: Imagine you are driving on a sunny day, and the sun reflects off the wet road ahead. This reflected light causes a bright, blinding glare. This glare is mostly horizontally polarized. If you wear polarized sunglasses, the vertically aligned filters in the lenses will block most of this horizontally polarized light. As a result, the glare disappears or is greatly reduced, allowing you to see the road markings and other vehicles clearly without straining your eyes. This is a direct application of Malus's law, where the sunglasses act as an analyzer that significantly reduces the intensity of the unwanted polarized light.

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

Ans: If there were no atmosphere, the sky would appear black, even during the day. This is because there would be no air molecules to scatter sunlight. The sun would appear as a very bright disk against a dark, star-filled sky, similar to how space looks from the Moon.

8.5 What is the significance of detecting gravitational waves?

Ans: Detecting gravitational waves is highly significant because it:

- **Confirms Einstein's General Relativity:** It provides strong observational evidence for a key prediction of Einstein's theory, strengthening our understanding of gravity.
- **Opens a New Window to the Universe:** It allows us to "hear" and "see" extreme cosmic events (like black hole mergers) that are invisible to traditional light-based telescopes. This is a new way to study the universe.
- **Studies Strong-Field Gravity:** It provides a way to observe gravity in its most extreme forms, where black holes and neutron stars distort space-time strongly.
- **Helps Understand Early Universe:** Gravitational waves could potentially carry information from the very early universe, before light could freely travel.
- **Tests Fundamental Physics:** It offers new ways to test fundamental theories of physics under conditions that cannot be replicated on Earth.

COMPREHENSIVE QUESTIONS

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

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

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

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

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

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

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

8.8 What is meant by optical activity? Discuss it.

SOLVED EXAMPLES

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 Refractive index $n=\sqrt{3}$

We need to find the angle of refraction θ_r

Using Brewster's Law: $\tan\theta_B=n$

$\tan \theta B = \sqrt{3}$

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

$\theta_B = 60^\circ$

At the polarizing angle, the reflected and refracted beams are at 90° to each other:

$\theta r = 90^\circ - \theta_B$

$\theta_r = 90^\circ - 60^\circ$

$\theta_r = 30^\circ$

Answer: The angle of refraction will be 30°.

EXAMPLE 8.2

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

Solution:

Given:

Polarizing angle $\theta p = 54.5^\circ$

We need to find the refractive index n.

Using Brewster's Law: $\tan\theta_p = n$

$n = \tan(54.5^\circ)$

$n = 1.4$

Answer: The refractive index of the medium is 1.4.

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:

Initial intensity $I0 = 75$ W m^{-2}

Angle $\theta = 30^\circ$

We need to find the emerging intensity I.

Using Malus's Law: $I = I_0 \cos^2\theta$

$I = 75 \text{ W m}^{-2} \times \cos^2(30^\circ)$

$I = 75 \text{ W m}^{-2} \times (0.866)^2$

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

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

Answer: The emerging intensity is 56.25 W m−2.

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:

Initial amplitude $A0 = 5$ units

Angle $\theta = 60^\circ$

We need to find the transmitted amplitude A.

Using the amplitude relation from Malus's law:

$A = A0\cos\theta$

$A = 5 \times \cos(60^\circ)$

$A = 5 \times 0.5$

$A = 2.5$ units

Answer: The amplitude of the wave after passing through the analyzer is 2.5 units.

EXAMPLE 8.5

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

Solution:

Given:

Wavelength $\lambda = 4000 \text{ km} = 4\times10^6$ m

Speed of light $c = 3\times108$ m s−1 (since GWs travel at the speed of light)

We need to find the frequency f.

Using the wave speed formula: $v = c = f\lambda$

$$\text{So, } f = \frac{c}{\lambda}$$

$$f = \frac{3\times10^8 \text{ m s}^{-1}}{4\times10^6 \text{ m}}$$

$$f = 0.75\times10^2 \text{ s}^{-1}$$

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

Answer: The frequency of the gravitational waves is 75 Hz.

Example 8.6

A binary system emits gravitational waves with a frequency of 10^{-7} Hz. What is the wavelength of these waves?

Solution:

Given:

Frequency $f = 10^{-7} \text{ Hz} = 10^{-7} \text{ s}^{-1}$

Speed of light $c = 3\times10^8$ m s^{-1} (since GWs travel at the speed of light)

We need to find the wavelength λ.

Using the wave speed formula: $c = f\lambda$

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

$$\lambda = \frac{3\times10^8 \text{ m s}^{-1}}{10^{-7} \text{ s}^{1}}$$

$$\lambda = 3\times10^{15} \text{ m}$$

Answer: The wavelength of these waves is 3×1015 m.

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.

Given

Intensity of unpolarized light = I_o

Intensity of polarized light = $I = I_o \cos^2\theta$

$$= I_o \cos^2 45 = I_o\left(\frac{1}{\sqrt{2}}\right)^2 = I_o\left(\frac{1}{2}\right) = \frac{I_o}{2}$$

Intensity of untransmitted light = $I_o - I$

$$= I_o - \frac{I_o}{2} = \frac{I_o}{2}$$

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

Given

Intensity of unpolarized light = I_o = 100 W m^{-2}

Angle of polarization = θ = 45°

Intensity of polarized light = I = ?

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

$$I = 100 \cos^2 45 = 100\left(\frac{1}{\sqrt{2}}\right)^2 = 100\left(\frac{1}{2}\right) = 50 \text{ W m}^{-2}$$

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?

Given

Amplitude of unpolarized wave = A_o = 10 units

Angle between the electric field and the polarizer = $\theta = 30^\circ$

amplitude of polarized wave = A = ?

Solution:

$$A = A_o \cos\theta$$

$$A = 10 \cos 30^\circ$$

$$A = 10\,\frac{\sqrt{3}}{2} = 8.66 \text{ units}$$

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%?

Intensity of incident light = I_o = 100% = 1

Intensity of transmitted light = I

= 100 − 85 = 15 % = 0.15

Angle of polarization = θ

By using Malus's law

$$0.15 = 1 \cos^2\theta$$

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

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

$$\theta = \cos^{-1}(0.39) = 67.5^\circ$$

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.

Given

Intensity of unpolarized light = I_1 = 15 W m^{-2}

First polarization angle = θ_1 = 50°

Second polarization angle = θ_2 = 20°

Angle of polarization = $\theta = \theta_1 - \theta_2 = 50 - 20 = 30^\circ$

To Find

Intensity of final transmitted light = I = ?

Solution

intensity of light becomes half after passing through first polarized filter

so

$$I_o = \frac{I_1}{2} = \frac{15}{2} = 7.5 \text{ Wm}^{-2}$$

Now using Malus's law

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

$$I = 7.5 \cos^2 30 = 7.5\left(\frac{\sqrt{3}}{2}\right)^2 = 7.5\left(\frac{3}{4}\right) \text{ m}^{-2}$$

$$= 5.6 \text{ W}$$

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?

Given

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

$$\theta = ?$$

Solution

By using Malus's law

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

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

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

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

$$\theta = \cos^{-1}\frac{1}{\sqrt{2}} = 45^\circ$$

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.

Given

Refractive index of glass plate = n = 1.5

To find

Polarizing angle = θ_p = ?

Angle of refraction = θ_r = ?

Solution

By using Brewster's law

$$\tan\theta_p = n$$

$$\theta_p = \tan^{-1} n$$

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

$$\theta_p = 56.3^\circ$$

Now

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

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

$$\theta_r = 90^\circ - 56.3^\circ = 33.7^\circ$$