Physical Optics and Gravitational Waves

TOPIC 1 Polarization of Light

SQ 8.1.1 With what does this chapter deal?

Answer

This chapter deals with two major areas of physics, namely polarization of transverse waves and gravitational waves.

SQ 8.1.2 With what does physical optics deal?

Answer

Physical optics with reference to polarization deals with the behaviour of light waves and their interaction with matter.

SQ 8.1.3 What is the plane of polarization?

Definition

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.

SQ 8.1.4 Of what does a light wave produced by an oscillating charge consist?

Answer

It consists of a periodic variation of the electric field vector $\mathbf{E}$, accompanied by the magnetic field vector $\mathbf{B}$ at right angles to it.

SQ 8.1.5 What is unpolarized light?

Definition

Ordinary light has components of vibration in all possible planes. Such light is unpolarized.

SQ 8.1.6 What is polarized light?

Definition

If the vibrations of light are confined only in one plane, the light is said to be polarized.

SQ 8.1.7 Give examples of unpolarized light sources.

Examples

Sunlight, incandescent light bulbs, fluorescent light bulbs, and light from a candle or fire.

SQ 8.1.8 Define polarization.

Definition

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

SQ 8.1.9 Why does polarization not occur in sound waves?

Reason

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

SQ 8.1.10 Name three methods by which unpolarized light can be polarized.

Methods

By passing light through a polarizing filter such as a polaroid sheet.
By using a polarizing beam splitter.
By employing certain optical crystals or materials, such as calcite and quartz.

SQ 8.1.11 How does a polarizing filter polarize light?

Working

When unpolarized light passes through the polarizing filter, only the electric field vector which is parallel to the axis of the filter can pass through it, while all other vectors are blocked.

Result

The resultant light then becomes polarized.

SQ 8.1.12 What is the basis of polarization?

Answer

The orientation of the electric field vector $\mathbf{E}$ of light waves in a specific direction is the basis of polarization.

TOPIC 2 Types of Polarization

SQ 8.2.1 Define linear polarization.

Definition

When the electric field vector oscillates in a single plane, the light is said to be linearly polarized.

Example

Light passing through a polarizing filter, like sunglasses.

SQ 8.2.2 Define circular polarization.

Definition

When the electric field rotates circularly, either clockwise (right-handed) or counterclockwise (left-handed), the light is said to be circularly polarized.

Example

Light reflected off a Compact Disc or a Digital Versatile Disc.

SQ 8.2.3 Define elliptical polarization.

Definition

Elliptical polarization is a combination of linear and circular polarization, where the electric field vector traces an elliptical path.

Condition

The two components E_x and E_y are not equal, or they differ in phase by an arbitrary angle.

Example

Light passing through a stress plate or a waveplate.

SQ 8.2.4 Differentiate between linear and circular polarization.

Linear Polarization	Circular Polarization
The electric field vector oscillates in a single plane.	The electric field vector rotates circularly.

Linear Polarization	Circular Polarization
Light through sunglasses is an example.	Light reflected off a CD is an example.

TOPIC 3 Production and Detection of Plane Polarized Light

SQ 8.3.1 Why is the light from an ordinary incandescent bulb unpolarized?

Reason

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

SQ 8.3.2 What are a polarizer and an analyzer?

Polarizer

The first sheet of polaroid on which unpolarized light is made incident, whose transmitted light is plane polarized.

Analyzer

A second sheet of polaroid placed after the polarizer to detect the polarized light.

SQ 8.3.3 What is observed when the axes of the two polaroids are parallel?

Answer

When the axes of the two polaroids are parallel, the light is transmitted through the second polaroid and is brightest.

SQ 8.3.4 What is observed when the analyzer is slowly rotated?

Answer

The light emerging from the second polaroid gets dimmer and dimmer and ultimately disappears when the axes become mutually perpendicular. The light reappears on further rotation.

SQ 8.3.5 What does the polaroid experiment prove?

Proof

This experiment proves that light waves are transverse waves.

Reason

If the light waves were longitudinal, they would never disappear even if the two polaroids were mutually perpendicular.

SQ 8.3.6 Can a polarizer be used as an analyzer?

Answer

Yes. An analyzer is also a polarizer that is placed after a polarizer, so the same sheet of polaroid can serve either purpose depending on its position in the arrangement.

TOPIC 4 Polarization of Light by the Method of Reflection

SQ 8.4.1 What did Malus discover in 1808?

Discovery

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

SQ 8.4.2 How is it shown that reflected light is plane polarized?

Method

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.

SQ 8.4.3 What is the most suitable angle of incidence for glass?

Answer

The most suitable angle of incidence is about 57° for glass, for which the reflected ray becomes plane polarized.

SQ 8.4.4 Give an everyday example of partial polarization by reflection.

Example

Light reflected from the surface of a table becomes darker when viewed through a rotated polaroid, showing that it is partially plane polarized.

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

SQ 8.4.5 Define the polarizing angle.

Definition

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

SQ 8.4.6 What is the relation between the reflected and refracted beams at the polarizing angle?

Answer

At the polarizing angle the reflected and refracted beams are at right angles to each other, so

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

SQ 8.4.7 Derive Brewster's law.

Derivation

From Snell's law

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

and since

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

we get

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

Result

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

SQ 8.4.8 Write Brewster's law when the first medium is air.

Derivation

If medium 1 is air then

$n_1 = 1$

and

$n_2 = n$

Result

$\tan\theta_p = n$

Thus the tangent of the angle of polarization is numerically equal to the refractive index of the medium.

SQ 8.4.9 What is the Brewster angle?

Definition

The angle θ_p for which the reflected ray and the refracted ray make an angle of 90° between them is called the Brewster angle.

SQ 8.4.10 Light strikes glass of refractive index √3 at the polarizing angle. Find the polarizing angle.

Solution

Using

$\tan\theta_p = n$

Calculation

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

Result

$\theta_p = 60^\circ$

SQ 8.4.11 For light incident on glass at a polarizing angle of 60°, find the angle of refraction.

Solution

Since

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

Calculation

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

Result

$\theta_r = 30^\circ$

SQ 8.4.12 Find the refractive index of a medium if its polarizing angle is 54.5°.

Solution

Using

$n = \tan\theta_p$

Calculation

$n = \tan 54.5^\circ$

Result

$n = 1.4$

SQ 8.4.13 What are the applications of Brewster's angle?

Applications

Brewster's angle is used to produce plane polarized light by reflection, and to remove glare from reflecting surfaces such as water, glass and roads, as is done by polaroid sunglasses.

TOPIC 5 Malus's Law

SQ 8.5.1 State Malus's law.

Statement

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 the polarizer.

Formula

$I = I_0\cos^2\theta$

SQ 8.5.2 What relation does Malus's law give?

Answer

Malus's law gives a mathematical relation between the intensity of light incident on the first polaroid (the polarizer) and the intensity of light obtained after passing it through the second polaroid (the analyzer).

SQ 8.5.3 What is the purpose of an analyzer?

Answer

An analyzer is used to further reduce the intensity of light, and also to adjust it by adjusting the angle of the analyzer with respect to the polarizer.

SQ 8.5.4 What are polaroids?

Definition

Certain transparent crystalline materials, like tourmaline and calcite crystals, are capable of confining vibrations of light waves in only one plane. Such materials are called polaroids, which have high directionality in crystal structure.

SQ 8.5.5 By which natural phenomena can light be polarized?

Answer

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

SQ 8.5.6 Derive Malus's law from the resolution of amplitude.

Derivation

When incident polarized light of amplitude A_0 strikes the analyzer at an angle θ, it is resolved into $A_0\cos\theta$ and $A_0\sin\theta$. The component $A_0\sin\theta$ is absorbed.

Since only

$A = A_0\cos\theta$

passes through, and $I \propto A^2$,

Result

$I = I_0\cos^2\theta$

SQ 8.5.7 What happens when the angle between polarizer and analyzer is zero?

Answer

If

$\theta = 0^\circ$

then

$I = I_0$

The intensity transmitted through the analyzer is equal to the initial light intensity that passes through the polarizer.

SQ 8.5.8 What happens when the angle between polarizer and analyzer is 90°?

Answer

If

$\theta = 90^\circ$

then

$I = 0$

The light is extinguished completely, so no light is allowed to pass through the analyzer.

SQ 8.5.9 Polarized light of 75 W m⁻² passes through an analyzer at 30°. Find the emerging intensity.

Solution

Using

$I = I_0\cos^2\theta$

Calculation

$I = 75 \times (\cos 30^\circ)^2 = 75 \times 0.75$

Result

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

SQ 8.5.10 **Polarized light of amplitude 5 units passes through a polarizer at 60°. Find the emerging amplitude.**

Solution

Using

$A = A_0 \cos\theta$

Calculation

$A = 5 \times \cos 60^\circ = 5 \times 0.5$

Result

$A = 2.5$ units

SQ 8.5.11 **Define optical activity.**

Definition

Optical activity is the ability of a substance to rotate the plane of polarization of light passing through it. The rotation is detected with a polarizer or analyzer.

SQ 8.5.12 **Give examples of optically active substances.**

Examples

Quartz crystals, cinnabar, sugar water, insulin and collagen are optically active substances.

SQ 8.5.13 **On what factors does the amount and direction of optical rotation depend?**

Factors

The type of substance.
The concentration of the substance.
The distance the light travels through it.
The wavelength of light.

SQ 8.5.14 **Why does optical activity occur?**

Reason

Optical activity occurs due to the asymmetric shape of molecules in the substance, such as being helical. A few millimetres thickness of such crystals will rotate the plane of polarization by many degrees.

SQ 8.5.15 **Give a practical use of optical activity.**

Use

Certain organic substances such as sugar and tartaric acid show optical rotation when in solution. This property can be used to determine their concentration in the solutions.

SQ 8.5.16 **Why is polarization important in optics and photonics?**

Answer

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

SQ 8.5.17 **How does polarization help in imaging and microscopy?**

Answer

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

SQ 8.5.18 **Give the medical applications of polarization.**

Applications

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

SQ 8.5.19 **How is polarization used in astronomy?**

Answer

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

SQ 8.5.20 **How are polarizers used in sky photography?**

Working

A camera used to photograph clouds is fitted with a polaroid, so the light coming from the sky is polarized.

Result

Polarizers reduce the glare and haze produced by scattering of light by small particles in the atmosphere, and enhance contrast by blocking excessive bright white light.

SQ 8.5.21 **How are polarizers used in stress analysis of materials?**

Working

When a material is stressed, its molecular structure changes, affecting the way it interacts with light, and interference patterns or fringes are formed.

Use

By shining polarized light through the transparent material, researchers can determine stress patterns, identify weaknesses or defects, and analyze optical properties.

SQ 8.5.22 **What is photoelasticity?**

Definition

The technique of analyzing the stress patterns of a material by shining polarized light through it is known as photoelasticity. It is widely used in engineering, materials science and quality control.

SQ 8.5.23 **Why are polaroid sunglasses better than ordinary sunglasses?**

Reason

Polaroid sunglasses are fitted with polarizing filters which block the partially polarized light reflected from surfaces such as roads and water.

Result

They therefore cut down glare, whereas ordinary sunglasses only reduce the overall brightness.

TOPIC 6 Gravitational Waves

SQ 8.6.1 **Define a gravitational wave.**

Definition

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

SQ 8.6.2 What are gravitational waves described as?

Description

Gravitational waves are 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.

SQ 8.6.3 Give a simple example to understand gravitational waves.

Example

If we throw a stone into a pond, the stone creates ripples on the water surface, which represents space-time. These ripples travel outward, carrying information about the stone, which represents the cosmic event.

SQ 8.6.4 What is a binary system in the context of gravitational waves?

Definition

A binary system is 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.

SQ 8.6.5 What are continuous gravitational waves?

Definition

When a single massive object spins with a constant rate, such as a neutron star, continuous gravitational waves are produced with a constant frequency and amplitude.

Source

White dwarf binary systems produce continuous gravitational waves.

SQ 8.6.6 What are compact binary inspiral gravitational waves?

Definition

They are produced by a binary system such as binary neutron stars, binary black holes, or a neutron star and black hole orbiting each other.

Characteristic

In this type there is a gradual increase in frequency and amplitude of the waves.

SQ 8.6.7 What are burst gravitational waves?

Definition

Burst gravitational waves are produced by violent events like supernovas, gamma-ray bursts or cosmic strings.

SQ 8.6.8 What are stochastic gravitational waves?

Definition

Stochastic gravitational waves are weak, random signals produced by the superposition of many weak gravitational wave sources, such as distant binary systems.

Property

These waves are the most difficult to detect.

SQ 8.6.9 Which observatories detect gravitational waves?

Answer

Gravitational waves can be detected by observatories like LIGO, the Laser Interferometer Gravitational wave Observatory in the USA, and Virgo, a large scale gravitational wave observatory in Cascina, Italy.

SQ 8.6.10 What information do gravitational waves from binaries carry?

Answer

The waves carry information about the system's mass, spin and merger dynamics, offering insights into these extreme cosmic objects, and they move with the speed of light.

SQ 8.6.11 What is a merger in the context of binary systems?

Definition

A merger is the collision and union of two massive objects resulting in one more massive single object. Mergers are among the most intense cosmic events.

SQ 8.6.12 How do gravitational waves propagate through the universe?

Answer

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 and travel freely through spacetime at the speed of light, weakening in intensity with distance.

SQ 8.6.13 On which properties of a system do the characteristics of gravitational waves depend?

Properties

The masses of the objects.
The orbital period and frequency.
The eccentricity of the orbit.

SQ 8.6.14 Define eccentricity and give its values for different orbits.

Definition

Eccentricity is a measure of the amount by which an object deviates from a perfect circle.

Values

$e = 0$

is a circular orbit, $0 < e < 1$ is an elliptical orbit,

$e = 1$

is a parabolic trajectory and $e > 1$ is a hyperbolic trajectory.

SQ 8.6.15 What is space-time distortion?

Definition

Gravitational waves passing through a body with mass can cause the body to experience periodic stretching and compressing, also known as space-time distortion.

SQ 8.6.16 What are tidal forces?

Definition

The effect of periodic stretching and compressing caused by a gravitational wave is known as tidal forces, and it is a result of the wave's oscillating nature.

SQ 8.6.17 **How are tidal forces formed?**

Formation

As the gravitational wave passes through a body, it causes the spacetime around the body to oscillate, leading to a periodic stretching and compressing of the body in the direction perpendicular to the wave's propagation.

Analogy

This effect is similar to how the tides on Earth are caused by the gravitational pull of the Moon and Sun.

SQ 8.6.18 **On what does the amount of stretching and compressing depend?**

Answer

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

SQ 8.6.19 **What is the amplitude of gravitational waves passing through the Earth?**

Answer

The amplitude of these waves is extremely small, typically of the order of 10^{-18} to 10^{-21} m. Therefore the distortion is incredibly tiny and requires extremely sensitive instruments to detect.

SQ 8.6.20 **What is the importance of gravitational waves despite their small amplitude?**

Answer

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.

SQ 8.6.21 **Does every accelerating object produce gravitational waves?**

Answer

Yes. Every physical object that accelerates produces gravitational waves, including vehicles and airplanes. However, the masses and accelerations of objects on the Earth are too small to make gravitational waves big enough to be detected.

SQ 8.6.22 **Gravitational waves have a wavelength of 4000 km. Find their frequency.**

Solution

Since

$v = c = f\lambda$

therefore

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

Calculation

$f = \frac{3 \times 10^8}{4 \times 10^6}$

Result

$f = 75\,\mathrm{Hz}$

SQ 8.6.23 **A binary system emits gravitational waves of frequency 10^{-4} Hz. Find their wavelength.**

Solution

Since

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

Calculation

$\lambda = \frac{3 \times 10^8}{10^{-4}}$

Result

$\lambda = 3 \times 10^{12}\,\mathrm{m}$

TOPIC 7 Interferometer

SQ 8.7.1 **What are the main differences between LIGO and a conventional interferometer?**

Differences

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

SQ 8.7.2 **What is the function of the laser in a gravitational wave interferometer?**

Answer

The laser produces a stable and high intensity beam of light.

SQ 8.7.3 **What is the function of the power recycling mirror?**

Answer

The 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.

SQ 8.7.4 **What is the function of the beam splitter and the mirrors?**

Beam Splitter

It divides the laser beam into two perpendicular beams.

Mirrors

They reflect the beams, creating two perpendicular arms.

SQ 8.7.5 **What is the purpose of the Fabry-Perot cavity?**

Answer

The Fabry-Perot cavity consists of two mirrors facing each other. The purpose of the cavity is to enhance the path length.

SQ 8.7.6 **What is the function of the photodetectors and arm cavities?**

Photodetectors

They measure the returning beams, detecting tiny phase shifts if any.

Arm Cavities

They enhance the laser light, increasing sensitivity.

SQ 8.7.7 **Explain the working of a gravitational wave interferometer.**

Working

A laser beam is split into two perpendicular beams, each travelling down two identical arms. The beams bounce off mirrors at the ends of each arm and return to the starting point, where they are recombined.

Detection

If a gravitational wave passes through, it causes a tiny disturbance in the distances between the mirrors, resulting in a phase shift between the two beams.

SQ 8.7.8 How is the gravitational wave finally detected?

Answer

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.

SQ 8.7.9 When were gravitational waves first observed and from what source?

Answer

On 14 September 2015 the universe's gravitational waves were observed for the first time. They came from a collision between two black holes and took 1.3 billion years to arrive at the LIGO detector in the USA.

SQ 8.7.10 Who received the Nobel Prize for the observation of gravitational waves?

Answer

Rainer Weiss, Barry C. Barish and Kip S. Thorne received the Nobel Prize in 2017 for their work on the observation of gravitational waves.

SQ 8.7.11 Which Pakistani scientist was a member of the gravitational wave team?

Answer

Dr. Nergis Mavalvala, a Pakistani-American astrophysicist and a professor at the Massachusetts Institute of Technology, was one of the team members.

SQ 8.7.12 Describe the Virgo detector.

Description

Virgo is another facility for measuring gravitational waves, working under the European Gravitational Observatory at Cascina near Pisa, Italy.

Comparison

Virgo is also an interferometer with two arms of $3\,\mathrm{km}$, whereas LIGO has $4\,\mathrm{km}$ arms. Its first detection was in 2017.

SQ 8.7.13 After what is the Virgo observatory named?

Answer

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 1500 galaxies about 50 million light years away.

SQ 8.7.14 What is a light year and what is its approximate value?

Definition

One light year is the distance which light travels in one year.

Value

$1\,\mathrm{LY} = 9.5$ billion km