Chapter

8 Physical Optics and Gravitational Waves

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

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

8.1 POLARIZATION OF LIGHT

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

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

In transverse mechanical waves, such as produced in a stretched string, the vibrations of the particles of the medium are perpendicular to the direction of propagation of the waves. The vibrations can be confined along vertical, horizontal or any other direction (Fig. 8.1). In each of these cases, the transverse mechanical wave is said to be

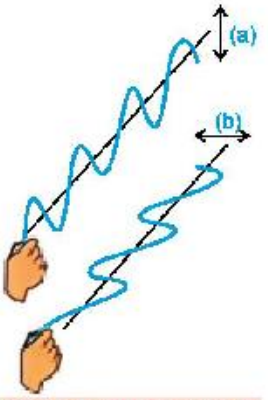

Fig. 8.1: Transverse waves on a string polarized
(a) In a vertical plane, and
(b) in a horizontal plane

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

A light wave produced by oscillating charge consists of a periodic variation of the electric field vector **E** accompanied by the magnetic field vector **B** at right angles to it. Ordinary light has components of vibration in all possible planes. Such a light is unpolarized. On the other hand, if the vibrations are confined only in one plane, the light is said to be polarized. Unpolarized light is shown in Fig. 8.2.

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

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

Polarization is the process by which the electric and magnetic vibrations of light waves are restricted to a single plane of vibration. It is the property exhibited only by transverse waves such as light waves. It does not occur for longitudinal waves such as sound waves.

How an Unpolarized Light be Polarized?

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

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

The most common method by which an unpolarized light can be polarized is by passing it through a polarizing filter, such as a polarizing beam splitter or a polaroid sheet. When an unpolarized light passes through the polarized filter, only that electric field vector which is parallel to the axis of polarized filter can pass through it, while all other vectors are blocked. The resultant light then becomes polarized as shown in Fig. 8.3.

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

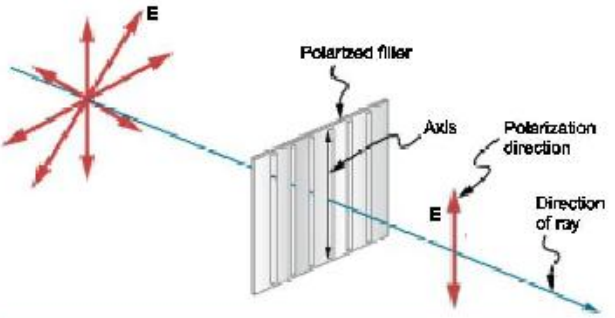

Fig. 8.3: Polarization of light using a polarized filter

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

8.2 TYPES OF POLARIZATION

Here are the basic types of polarization of light.

1. Linear Polarization

When the electric field vector oscillates in a single plane, light is said to be linearly polarized as shown in Fig.8.4 (a). Example is the light passing through a polarizing filter, like sunglasses.

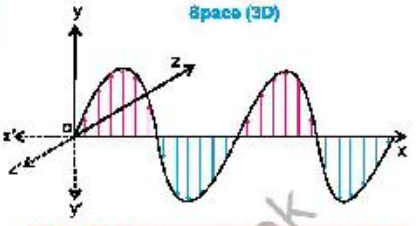

Fig. 8.4 (a): Linear polarization of light

2. Circular Polarization

When the electric field rotates circularly, either clockwise (right-handed), or counterclockwise (left-handed), the light is said to be circularly polarized as shown in Fig.8.4 (b). Example is the light reflected off a CD (Compact Disc) or DVD (Digital Versatile Disc).

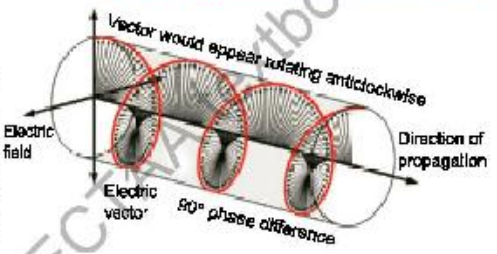

Fig. 8.4 (b): Circular polarization of light

3. Elliptical Polarization

A combination of linear and circular polarization, where the electric field vector traces an elliptical path is called elliptical polarization. In elliptical polarization as shown in Fig.8.4(c), the two components of electric field E_x and E_y are not equal or they differ in phase by an arbitrary angle θ. Example is the light passing through a stress plate or a waveplate.

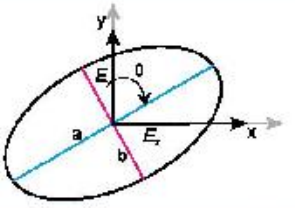

Fig. 8.4 (c): Elliptical polarization of light

8.3 PRODUCTION AND DETECTION OF PLANE POLARIZED LIGHT

The light emitted by an ordinary incandescent bulb is unpolarized, because its electrical vibrations are randomly oriented in space as shown in Fig.8.2.

If unpolarized light is made incident on a sheet of polaroid (polarizer), the transmitted light will be plane polarized. If a second sheet of polaroid (analyzer) is placed in such a way that the axes of the two polaroids shown by straight lines drawn on them are parallel (Fig. 8.5-a), the light is transmitted through the second polaroid. If the second polaroid (analyzer) is slowly rotated about the beam of light as axis of rotation, the light emerging from the second polaroid gets dimmer and dimmer and ultimately disappears when the axes become mutually perpendicular as shown in Fig. 8.5(b), the light reappears on

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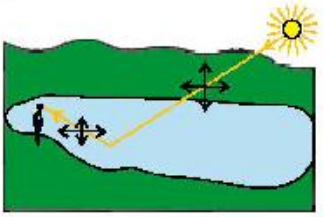
further rotation and becomes brightest when the axes are again parallel to each other.

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

Ponder Upon!



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

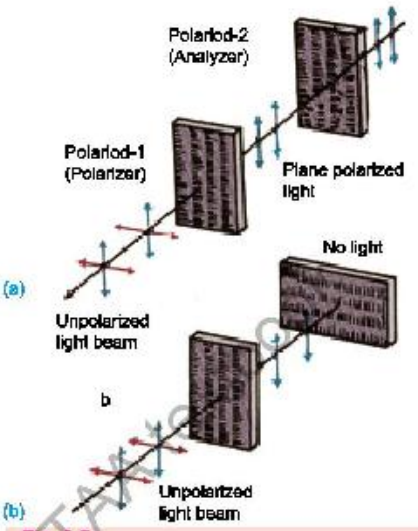


Fig. 8.5: Experimental arrangement to show that light waves are transverse. The lines with arrows indicate electric vibrations of light waves.

8.4 POLARIZATION OF LIGHT BY THE METHOD OF REFLECTION

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

Ray Diagram

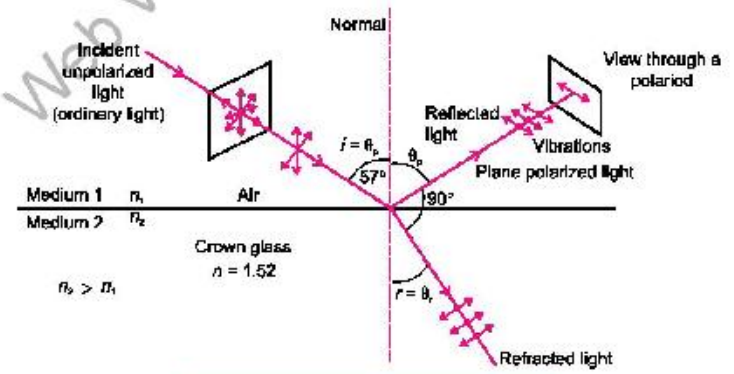


Fig. 8.6: Plane polarization by reflection

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orientation of the polaroid. The most suitable angle of incidence 'i' is about 57° for glass for which the reflected ray becomes plane polarized, as illustrated by ray diagram in Fig. (8.6). This proves that the light reflected by the glass is practically plane polarized. Light reflected from the surface of a table becomes darker when viewed through a rotated polaroid, showing that it is partially plane polarized.

Brewster's Law

The particular angle of incidence on a transparent medium when the reflected light is almost plane polarized is called the polarizing angle. Let a beam of unpolarized light be made incident on the surface of medium 2 as shown in Fig.8.6. If the reflected beam of light is almost plane polarized, the reflected and refracted beams are at right angles to each other at the polarizing angle, $i = \theta_p$. Thus

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

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

From Snell's law,

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

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

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

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

$$\tan\theta_p = \frac{n_2}{n_1} \quad \ldots\ldots\ldots\ldots\ldots (8.1)$$

Interesting information

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

This equation is known as Brewster's law. In this equation, n_1 is refractive index of medium 1 and n_2 is refractive index of medium 2. If medium 1 is air, then equation becomes $\tan\theta_p = n$ because $n_1 = 1$ and $n_2 = n$. Here n is refractive index of medium on which light is incident. Hence, Brewster proved that the tangent of the angle of polarization is numerically equal to the refractive index of the medium 2 when medium 1 is air. In Brewster's law, the angle 'θ_p' for which the reflected ray and the refracted ray make an angle of 90° between them, is also called the Brewster angle θ_B. Then, $\tan\theta_B = n$ holds.

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

Solution

$n = \sqrt{3}$, $\theta_r = ?$

As $\tan\theta_B = n$

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

$\theta_B = 60^\circ$

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

$\theta_r = 30^\circ$

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8.5 MALUS'S LAW

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 polarizer. That is;

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

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

where I_o = Intensity of the incident polarized light.

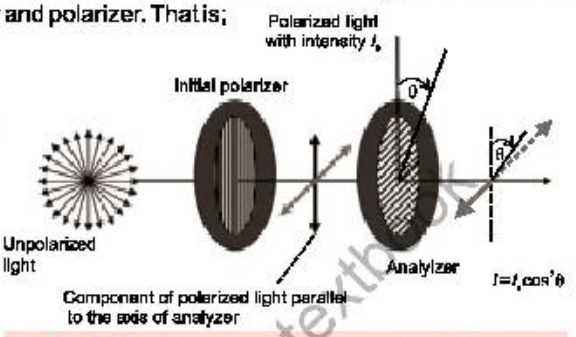

Fig. 8.7 (a): Schematic representation of Malus's law

Actually, Malus's law gives a mathematical relation between the intensity of the light incident on the first polaroid (i.e., polarizer) and the intensity of light obtained after passing it through the second polaroid (i.e., analyzer). This is shown in Fig. 8.7(a). An analyzer is also a polarizer that is placed after a polarizer. Rotation of the analyzer affects the intensity of the polarized light. It is used to further reduce the intensity of light and also adjust it by adjusting the angle of the analyzer with respect to the polarizer.

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

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

When the incident polarized light of amplitude A_o strikes the analyzer at an angle θ, it is resolved into two components $A_o\cos\theta$ and $A_o\sin\theta$ as shown in Fig. 8.7(b). The component $A_o\sin\theta$ is absorbed in the analyzer. Since, only $A_o\cos\theta$ passes through the analyzer, the amplitude A of the transmitted light is therefore,

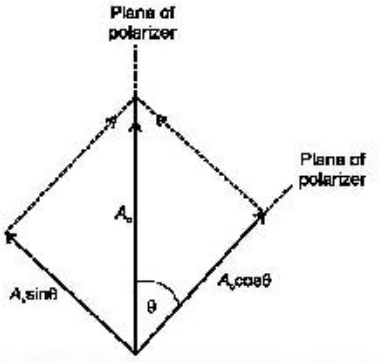

Fig.8.7(b): Resolution of amplitude into components of plane polarization light.

$$A = A_o\cos\theta \quad \text{..... (8.2)}$$

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

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$I \propto A^2$ or $I = kA^2$

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

or $I = A_o^2 \cos^2\theta$

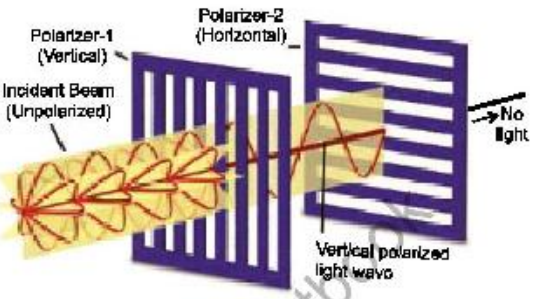
$I = I_o \cos^2\theta \quad (\because I_o = A_o^2)$

Here I_o is the intensity of the incident polarized light.

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

i. If $\theta = 0°$, then $I = I_o$. This means the intensity transmitted through the analyzer is equal to the initial light intensity that passes through the polarizer.

For your information



Light passing through crossed polarizers

ii. If $\theta = 90°$, then $I = 0$. This means the light is extinguished completely, i.e., no light is allowed to pass through the analyzer.

Optical Activity

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 as shown in Fig. 8.8.

Many crystals and solutions rotate the plane of polarization of light passing through them. Such substances are said to be optically active. Examples are quartz crystals, cinnabar (H_gS), sugar water, insulin and collagen. The amount and direction of rotation depends on following factors:

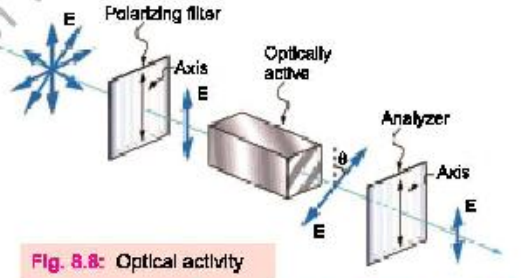


Fig. 8.8: Optical activity

(i) The type of substance

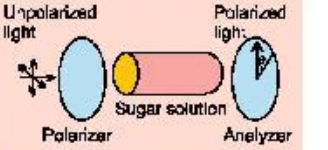
(ii) The concentration of the substance (the amount of a substance present in a given quantity of a mixture or solution).

(iii) The distance the light travels through it, and

(iv) The wavelength of light.

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

Interesting Information



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

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of polarization by many degrees. Certain organic substances, such as sugar and tartaric acid, show optical rotation when they are in a solution. This property of optically active substances can be used to determine their concentration in the solutions.

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

Solution

$\theta_p = 54.5°, n = ?$

As $\tan\theta_p = n$

or $n = \tan\theta_p$

So $n = \tan 54.5°$

$n = 1.4$

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

$I_o = 75\ W\ m^{-2}, \theta = 30°, I = ?$

Using Malus's law:

$I = I_o \cos^2\theta$

$I = 75\ N\ m^{-2} \cos^2 30°$

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

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

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

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 analizer?

Solution

$A_o = 5$ units, $\theta = 60°, A = ?$

Using Malus's law:

$A = A_o \cos\theta$

or $A = 5 \cos 60°$

$= 5 \times 0.5$

$A = 2.5$ units

Do you know?

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

Tidbit

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

Importance of Polarization

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

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1. Optics and Photonics

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

2. Imaging and Microscopy

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

3. Medical Applications

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

4. Astronomy

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

5. Miscellaneous Fields

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

Two Main Applications of Polarization

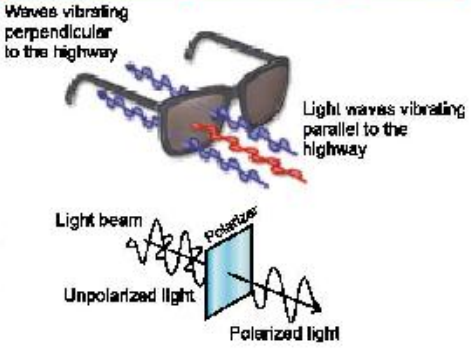
Polarizers, also known as polarizing filters, have two main applications:

1. Sky Photography

A camera which is used to photograph the clouds is fitted with a polaroid. The light coming from the sky is polarized by the polaroid.

In sky photography, polarizers are used to reduce the glare and haze which are produced by the scattering of light by small particles of molecules present in the atmosphere. Polarizers also enhance the contrast by clocking the excessive bright white light while allowing the other colours to pass through, thus creating a brighter detailed image. Thus, allows to improve the overall image quality.

Action of polarized sunglasses



2. Stress Analysis of Materials

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

When a material is stressed, its molecular structure changes, affecting the way, it

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interacts with light, and interference patterns on fringes are formed which in turn gives qualitative information about the material. By shining polarized light through the transparent material and analyzing the changes in the light's polarization, the researchers can:

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

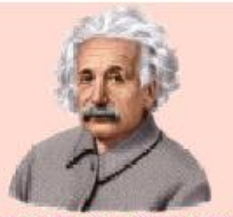
In both cases described above, polarizers play a crucial role in manipulating light to achieve specific goals, whether it is enhancing image quality or analyzing material properties.

8.6 GRAVITATIONAL WAVES (GWs)

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

Gravitational waves (GWs) are actually:

"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."



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

The simplest example to understand GWs is given below:

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

Prediction and Detection

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

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

Gravitational waves, as initially predicted by Albert Einstein in 1916, are ripples in spacetime that were first detected in 2015, but announced in 2016, the first

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observation of its kind: the detection of gravitational waves, produced from two colliding neutron stars. In this type, there is a gradual increase in frequency and amplitude of GWs.

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

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

Four Basic Types of GWs

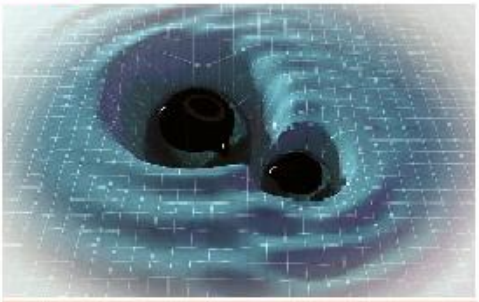
There are four basic types of gravitational waves, each with different sources and characteristics:

1. Continuous GWs

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

2. Compact Binary Inspirational GWs

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



BS Model

3. Burst GWs

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

4. Stochastic GWs

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

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

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

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

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

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

Tidal forces carry the mathematical signature of gravitational waves

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

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

$e = 0$	Circular orbit
$e = 1$	Parabolic trajectory
$e > 1$	Hyperbolic trajectory
$0 < e < 1$	Elliptical orbit

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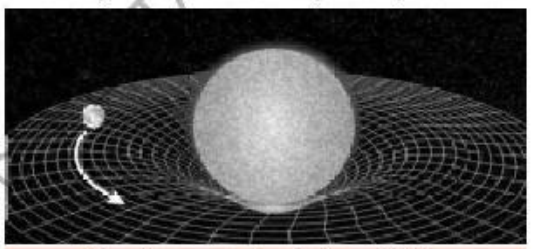
Space-time Distortion / Tidal Forces

Gravitational waves passing through a body with mass can cause the body to experience periodic stretching and compressing, also known as "space-time distortion". This effect is known as "tidal forces" and is a result of the gravitational wave's oscillating nature. As the gravitational wave passes through the body, it causes the space-time around the body to oscillate, leading to a periodic stretching and compressing of the body in the direction perpendicular to the wave's propagation. This effect is similar to how the tides on Earth are caused by the gravitational pull of the Moon and Sun.

Spacetime curve of an artificial and a natural satellite

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

Gravitational waves generated by far off celestial events, such as the merger of two black holes or neutron stars, pass through the Earth. However, the amplitude of these waves is extremely small, typically of the order of 10^{-21} to 10^{-22} metres. This means that the distortion caused by the gravitational wave is incredibly tiny, and requires extremely sensitive instruments to detect.



Spacetime curve shown by two satellites

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

8.7 INTERFEROMETER

An interferometer is an optical tool used in detecting gravitational waves. It is a very sensitive detection device that may use the interference of LASER (Light Amplification by Stimulated Emission of Radiatoin) beams. The basic LIGO interferometer can be seen in Fig. 8.9.

An interferometer that detects gravitational waves is a highly sensitive instrument that uses LASER light to measure tiny changes in distance between mirrors, caused by gravitational waves passing through the detectors. These interferometers are called

LIGO (LASER Interferometer Gravitational Wave Observatory). The main differences between LIGO and conventional interferometers are:

(a) LIGO is 1000 times larger than conventional device, and

(b) LIGO uses LASER whereas conventional interferometer has normal light source.

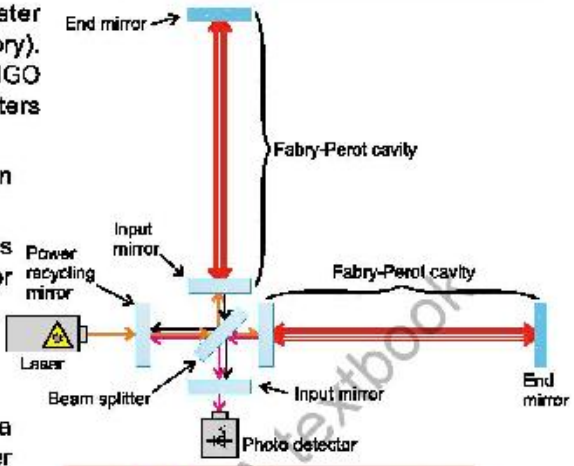


Fig. 8.9: Basic LIGO Interferometer

Basic Components of GW Interferometer

The basic components of a gravitational wave interferometer are:

1. **Laser** that produces a stable and high intensity beam of light.
2. **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.
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. The purpose of the cavity is to enhance the path length.
6. **Photodetectors** measure the returning beams, detecting tiny phase shifts (if any).
7. **Arm cavities** enhance the LASER light, increasing sensitivity.

Working of Interferometer

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

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

Figure 8.9 is a simple figure of an interferometer, but in reality, it is much more complex. On 14 September 2015, the universe's gravitational waves were observed for the very first time by LIGO. The gravitational waves which were predicted by Albert Einstein

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100 years ago, came from a collision between two black holes. It took 1.3 billion years for the waves to arrive at the LIGO detector in the USA. On their work on observation of GWs, Rainer Weiss, Barry C. Barish and Kip S. Throne received Nobel Prize in 2017. It is interesting to note that one of the team members, Nergis Mavalwala a professor at MIT (Massachusetts Institute of Technology), belongs to Pakistan.

Virgo Detection

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

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

Solution $\lambda = 4000\ \text{km} = 4\times10^{6}\ \text{m}$, $c = 3\times10^{8}\ \text{m s}^{-1}$, $f = ?$

As $v = f\lambda$

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

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

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

$f = 75\ \text{Hz}$

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

Solution $f = 10^{-1}\ \text{Hz} = 10^{-1}\ \text{s}^{-1}$, $c = 3\times10^{8}\ \text{m s}^{-1}$, $\lambda = ?$

As $v = f\lambda$

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

$\therefore\quad \lambda = \dfrac{3\times10^{8}\ \text{m s}^{-1}}{10^{-1}\ \text{s}^{-1}}$

$\lambda = 3\times10^{9}\ \text{m}$

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QUESTIONS

Multiple Choice Questions

Tick (✓) the correct answer.

8.1 The phenomenon of polarization of light is:

(a) the process of scattering of light
(b) the property of light to vibrate in a specific plane
(c) the ability of light to travel in a straight line
(d) the phenomenon of light changing colour

8.2 Malus's law states that:

(a) the intensity of light is directly proportional to the square of the cosine of the angle between the light wave and the analyzer
(b) the intensity of light is directly proportional to the square of the sine of the angle between the light wave and the analyzer
(c) the intensity of light is directly proportional to the angle between the light wave and the analyzer
(d) the intensity of light is inversely proportional to the angle between the light wave and the analyzer

8.3 The intensity of light when it passes through a polarizer:

(a) increases (b) decreases
(c) remains the same (d) becomes zero

8.4 The angle between the light wave and the analyzer is called:

(a) polarization angle (b) refraction angle
(c) reflection angle (d) azimuth angle

8.5 The key purpose of an analyzer in a polarization experiment is:

(a) to polarize the light (b) to measure the intensity of light
(c) to change the direction of light (d) to filter out unwanted light

8.6 The mathematical representation of Malus's law is:

(a) $I = I_0 \cos^2\theta$ (b) $I = I_0 \sin^2\theta$
(c) $I = I_0 \tan^2\theta$ (d) $I = I_0 \cot^2\theta$

8.7 The effect of increasing the angle between the light wave and the analyzer on the intensity of light is:

(a) the intensity increases (b) the intensity decreases
(c) the intensity remains the same (d) the intensity becomes zero

8.8 The condition for maximum intensity of light in a polarization experiment is when:

(a) the light wave and analyzer are perpendicular
(b) the light wave and analyzer are parallel
(c) the light wave and analyzer are at an angle of 45°
(d) the light wave and analyzer are at an angle of 60°

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

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

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

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

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

Short Answer Questions

8.1 Why are the polaroid sunglasses better than the ordinary sunglasses?
8.2 Is light from the sky partially polarized? How is it so?
8.3 How is Malus's law used in everyday life?
8.4 What are the applications of Brewster's angle?
8.5 What is the space-time curvature?

Constructed Response Questions

8.1 Write down some applications of plane polarized.
8.2 Would it be possible to use a polarizer as an analyzer? If yes, give at least two examples.
8.3 Explain how Malus's law is used in the design of polarized sunglasses. How do these surfaces reduce glare from reflective surface? Provide an example to illustrate your answer.
8.4 How will the sky appear if there had been no atmosphere?
8.5 What is the significance of detecting gravitational waves?
8.6 How are tidal forces formed?

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.

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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.

Numerical Problems

8.1 When an unpolarized light of intensity I_o is incident on a polarizing sheet, find the intensity of light which does not get transmitted. (Ans: $\frac{I_o}{2}$)

8.2 A polarized light beam passes through a polarizer at an angle of 45°. Find the intensity of the transmitted light if the initial intensity is 100 W m^{-2}. (Ans: 50 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? (Ans: 8.66 units)

8.4 What angle is required between the direction of polaroid light and the axis of a polaroid filter to reduce its intensity by 85%? (Ans: 67.5°)

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. (Ans: 7.5 W m^{-2}, 5.6 W m^{-2}, respectively)

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? (Ans: 45°)

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. (Ans: 56.3°, 33.7°, respectively)

8.8 At what angle of incidence, will light reflected from water be completely polarized? (Ans: 53°)

8.9 A beam of unpolarized light is incident on a stack of four polarizing sheets that are lined up so that the characteristic direction of each is rotated by 30° clockwise with respect to the preceding sheet. What fraction in percentage of the incident intensity be transmitted? (Ans: 21%)

8.10 A polarizer and an analyzer have their axes aligned at 60°. What is the fraction of the initial intensity that emerges? (Ans: 0.25)

8.11 If the gravitational waves have a wavelength of 3000 km, then find their frequency assuming it moves with the speed of light? (Ans: 100 Hz)

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