Unit - 12
Electromagnetic Spectrum

Students' Learning Outcomes (SLOs)

After learning this unit, students should be able to

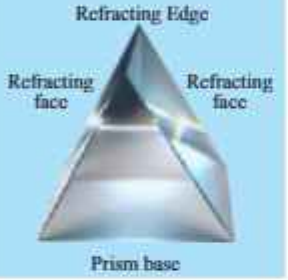
- Describe the dispersion of light as illustrated by the action on the light of a glass prism
- State the colors of the spectrum and explain how the colors are related to frequency/wavelength.
- Describe the behavior of light when passing through water droplets.
- State that all electromagnetic waves travel with the same high speed in air and state the magnitude of that speed.
- Describe the main components of the electromagnetic spectrum.
- Discuss the role of the following: (i) radio waves – radio and television communications, (ii) microwaves – satellite television and telephone, (iii) infra-red – household electrical appliances, television remote controller, and intruder alarms, (iv) light – optical fibers in medical uses and telephone, (v) ultra-violet – sunbeds, fluorescent tubes, and sterilization, (vi) X -rays – hospital use in medical imaging and killing cancerous cells, and engineering applications such as detecting cracks in metal, (vii) gamma rays – medical treatment in killing cancerous cells, and engineering applications such as detecting cracks in metal.

May 16, the International Day of Light

UNESCO celebrates the role of light in science, education. It plays an essential role in our lives. It is the origin of life through photosynthesis on its most fundamental level. The light has led us to alternative energy sources and many other discoveries that have shaped our understanding of the Universe. For centuries, the study of light and its properties has revolutionized every science discipline, from Ibn Al Haytham to Einstein. From gamma rays to radio waves, the spectrum of light provides understandings both far-ranging and near.

Do You Know!

The prism is a triangular transparent block of glass or plastic. It is a solid structure having three rectangular and two triangular surfaces.



We live in a technologically advanced world, where more and more electronic appliances are going wireless. We use mobile phones, laptops, and even mobile televisions. It seems like these cordless appliance scans detect and read information from our surroundings, and we can also communicate and share digital information through electronic media. Where does all this information come from? How does this information travel through in air or a vacuum? We will try to understand all this in detail.

12.1 Dispersion of light

Have you ever seen the rainbow? What the physics behind this phenomenon is; Let us learn it by using a glass prism. Suppose a narrow beam of white light entering from the air is passed through a prism of the denser medium. A prism refracts the light at both the refracting surfaces, and it produces a range of colors called a spectrum.

Splitting white light into its constituent colors when it passes through a glass prism is called dispersion of white light.

White light is not a single color but a mixture of all the spectrum colors. The prism refracts each individual color differently depending on their refractive index.

The spectrum of White light

When a narrow beam of white light splits, the color sequence produced in the spectrum is indicated by the acronym V I B G Y O R, which stands for Violet, Indigo, Blue, Green, Yellow, Orange, and Red, as shown in figure 12.1. The speed and direction of white light vary depending on the wavelength. The red color has a maximum speed in the glass prism, with the slightest deviation. In contrast, the violet color has minimum speed, which with most deviation because color has its own refracted path in the air and becomes distinct on the spectrum.

The color pattern produced in the dispersion is called a spectrum of light.

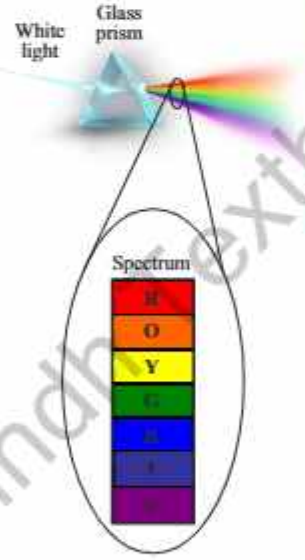


Fig: 12.1
Dispersion of white light by a glass prism

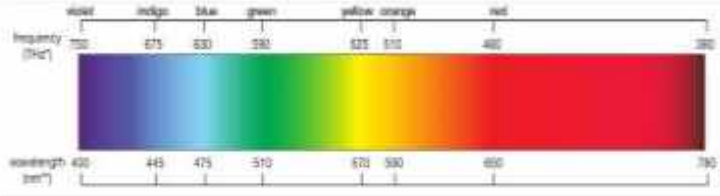


Figure: 12.2 Spectrum of visible light with corresponding wavelengths and their frequencies of each color

Table: 12.1.
Index of Refraction in crown glass at Various Wavelengths. The table shows different colors have different wavelengths so, as the refractive index

Color	Wavelength/ nm	Refractive Index
Red	650	1.332
Orange	625	1.333
Yellow	575	1.334
Green	525	1.336
Blue	450	1.340
Indigo	425	1.342
Violet	400	1.344

Do You Know!

The red color is used in the traffic signals. Red light has the highest wavelength of all the colors, and the air molecules least scatter it. So, it can travel the longest distance and penetrate through rain, mist, and fog. This is why red is being used in traffic signals to make the stop signal visible from a far distance.

Dispersion of light through water droplets

The rainbow is one of nature's most beautiful creations. When a rainbow appears, it serves as an excellent demonstration of light dispersion and further evidence that visible light has a spectrum of wavelengths, each of which is associated with a distinct color. At an angle of approximately 40 degrees above ground level, you must look into an area of atmosphere with suspended droplets of water, or even a light mist, in order to see a rainbow in the sky. Every droplet of water acts as a tiny prism, dispersing and reflecting light to your eye. When you look at the sky, droplets emit wavelengths of light associated with a color. There are several ways sun rays can enter through a drop. The bending toward and away from the normal is a defining characteristic of each and every path. The path of light as it enters the droplet, internally reflects, and then refracts out of the droplet is an important consideration when discussing rainbows. Figure 12.3 shows the complete process of dispersion of light through water droplet.

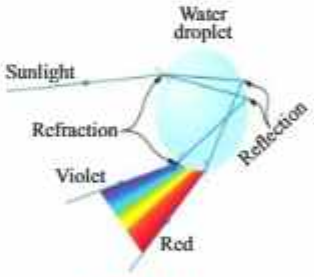


Fig: 12.3.
The dispersion by a water droplet

Do You Know!

When you listen to the radio, watch TV or make food in a microwave oven, you use electromagnetic waves.

Speed of electromagnetic waves

Electromagnetic waves are radiated out when charged particles oscillate. For example, vibrating atoms in a hot, glowing bulb filament emit infrared and visible light in the house. An oscillating electric current sends out radio waves from a radio station. The other types of EM radiation that make up the electromagnetic spectrum are microwaves, ultraviolet light, X-rays, and gamma rays that radiate out from their respective sources.

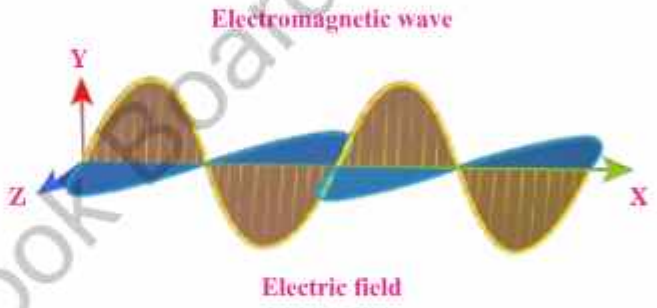
Electromagnetic waves are transverse waves. It is electric and magnetic fields that are oscillating, not material. Thus, they can travel through a vacuum or space.

Do You Know!

Light-year is the distance that light travels in one year. Light travels through interstellar space at 300,000 kilometers per second.

1 year = 365 days
= 365× 24 days
= 365× 24× 60 minutes
= 365× 24× 60× 60 seconds
= 31536000 seconds

1 light year = Velocity × Time
= 300000km/s × 31536000s
= 9.46×10^{12} m.



Like all other waves, it obeys the equation

Speed = frequency × wavelength

$$c = f \times \lambda$$

All electromagnetic waves travel through the space or vacuum at the same speed of 300000 kilometers per sec or 3×10^8 m.s^{-1}.

Worked Example 1

Ruby laser emits the beam of red light having a wavelength of 694.3 nm. Calculate its frequency.

Solution:

Step 1: Write down the known quantities and quantities to be found.

$\lambda = 694.3$ nm $= 694.3 \times 10^{-9}$m

$\lambda = 6.93 \times 10^{-7}$m

f=? and we know that

$c = 3 \times 10^8$ m.s^{-1}.

Step 2: Write down the formula and rearrange if necessary

$v = \lambda f$, and

$f = c/\lambda$

Step 3: Put the values and calculate.

Speed= wavelength × frequency

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

or $f = (3\times10^{8}\text{m/s})/(6.943\times10^{-7}\text{m})$

Result: $f = 4.32\times10^{14}\text{Hz}$

The frequency produced by the laser is 4.32×10^{14} Hz.

Do You Know!

Electromagnetic waves can travel through a transparent medium at different speeds according to their respective refractive index.

SELF-ASSESSMENT QUESTIONS :

Q1: A ray of blue light deviates more than a ray of red when passing through a prism. Explain why?

Q2: Give the sequence of colors produced in the dispersion through a prism.

Q3: X-rays have a higher frequency than radio waves. What is their speed in space?

12.2 Characteristics of electromagnetic waves

Some of the common characteristics of electromagnetic waves are given as under;

1. Electromagnetic waves are transverse waves in nature. They are composed of varying electric and magnetic fields that oscillate perpendicularly. The direction of wave motion is perpendicular to both electric and magnetic fields.
2. It can not carry electric charge.
3. It can travel through space, traveling at the speed of $c = 3\times10^{8}\ \text{m.s}^{-1}$.
4. It will travel through a transparent medium; however, they will slow down when traveling through a denser medium like water or glass.
5. It obeys the laws of reflection, refraction, and diffraction.
6. Its frequencies depend only on the source that produces the wave. Thus, frequencies do not change when it travel from one medium to another (air to glass).

Do You Know!

Ultraviolet radiation from the electromagnetic spectrum can not be seen, but it tans our skins and causes some substances to become fluorescent.

Main components of the electromagnetic spectrum

The electromagnetic spectrum has a wide range of frequencies, wavelengths, and energies. The spectrum covers the range of all electromagnetic radiation and consists of many sub-ranges that are generally referred to as components, such as visible light or ultraviolet radiation. There are no precise accepted boundaries between these continuous portions, so the ranges may tend to overlap.

The electromagnetic spectrum is the entire distribution of electromagnetic waves according to their frequencies or wavelengths.

Do You Know!

The electromagnetic waves of higher frequencies, such as X-rays or gamma rays, are more hazardous due to their higher energies (or higher frequencies)

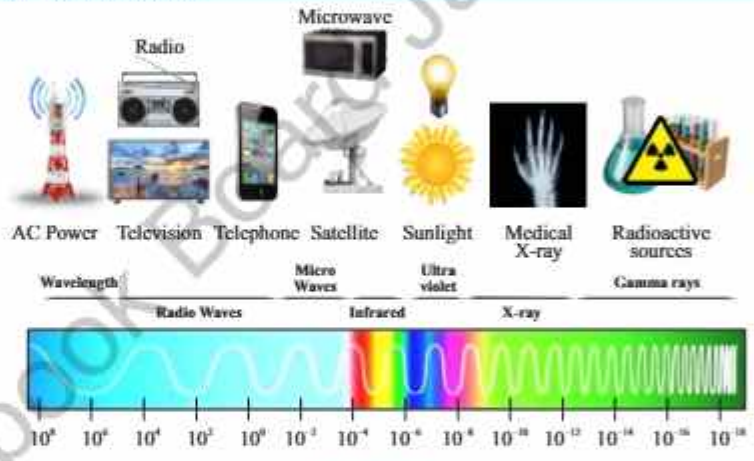


Fig: 12.4.
The electromagnetic spectrum with decreasing wavelengths as well comparison of wavelengths with the size of objects

Do You Know!

Radio waves have the longest wavelength in the electromagnetic spectrum.

From the lowest to the highest frequency or longest to shortest wavelength, the entire electromagnetic spectrum contains all radio waves, microwaves, infrared radiation, visible light, ultraviolet radiation, X-rays, and gamma rays. Radio waves have the longest wavelength, and gamma rays have the shortest wavelength.

Table 12.2 Electromagnetic Spectrum

Type of Electro-Magnetic wave	Sources	Applications
Radio and TV	Accelerating point charges	Communications, remote control devices, Magnetic Resonance Imaging (MRI)
Microwaves	Accelerating point charges and thermal agitation	Communications, microwave ovens, radar, Stelication
Infrared	Thermal agitations and electronic transitions	Heating, Heat therapy, Thermal imaging,
Visible light	Thermal agitations and electronic transitions	All pervasive, optical fiber, Human vision, Photosynthesis
Ultraviolet	Thermal agitations and electronic transitions	Cancer Control, Sterilization Sunbeds, Vitamin D production
X-rays	Inner electronic transitions and fast collisions	Imaging, Cancer therapy, Medical diagnosis
Gamma rays	Nuclear decay	Nuclear medicine, Radiography, Cancer therapy

Microwave oven

RADAR

Optical fiber

Fig: 12.5.
Some examples for application of EM spectrum

SELF-ASSESSMENT QUESTIONS:

Q1: State two different components of the electromagnetic spectrum that have wavelengths more significant than the wavelengths of red light.

Q2: State at least four properties common to all electromagnetic waves.

12.3 Uses of electromagnetic waves

Electromagnetic waves have many advanced technological uses in our day-to-day life. Some of the implied uses of the main components of the spectrum are given shortly below;

(i) Radio waves – radio and television communications

Radio waves have the longest wavelengths in the electromagnetic spectrum. Stars are natural transmitters of radio waves. However, radio waves can be artificially

generated by oscillating the current in a transmitting antenna. In a radio system, a microphone controls the current to the antenna so that the radio waves pulsate. The incoming pulsations in the radio receiver control a loudspeaker to create a copy of the original sound. Radio waves can diffract around hills, so radio can receive signals even if a hill blocks the direct route from the transmitting antenna. **Long waves** will also diffract around the curved surface of the Earth.

Radio waves are also used in television communication. Radio waves of very high-frequency **VHF** and ultra high-frequency **UHF waves** are used to telecast television programs. These waves have shorter wavelengths, and they do not diffract around hills. So, there must be a straight path between the transmitting and receiving antenna for good reception.

(ii) Microwaves – satellite television and telephone,

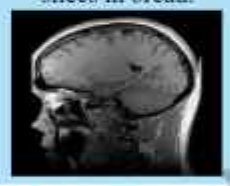
Microwaves have a shorter wavelength in the micrometer range and a higher frequency than all radio waves. These are usually generated inside the specialized oven by an electron tube. Satellite phones use microwaves for communication, and satellite television uses microwaves to receive satellite television programs. Microwaves can penetrate haze, light rain, clouds, and smoke as they have a higher frequency of all ranges of radio waves. However, because these waves are highly directional, the satellite dish and related components must be aligned appropriately, without any obstruction between the transmitted satellite signals and receiving satellite dish.

(iii) infra-red – household electrical appliances, television controllers and intruder alarms,

Infrared (IR), or infrared light, is electromagnetic radiation (EMR) with wavelengths longer than visible light. Infrared radiation is radiated or absorbed by molecules when they change their rotational-vibrational movements. Infra-red wireless remote controllers control various household electrical appliances that send invisible signals to an infrared receiver on a device such as televisions, video recorders, or hi-fi (High fidelity) systems.

Do You Know!

Magnetic resonance imaging (MRI) is advanced medical imaging technique that uses computer-generated radio waves and magnetic fields to create meticulous images of the organs and tissues in the body. When the patient lies inside an MRI machine, the magnetic field temporarily realigns water molecules in the body. Radio waves cause these aligned molecules to produce faint signals, computed to produce 3-D MRI images — like slices in bread.



Do You Know!

Bluetooth is a short-range wireless technology standard used to exchange data between fixed and mobile devices over short distances. Blue tooth using UHF radio waves. **Wi-Fi** is a networking technology that uses radio waves to allow high-speed data transfer over short distances.

The human body also gives out infrared radiations because of the rotational-vibrational motion of its atoms or molecules that motion sensors can detect. Intruder alarms use these motional sensors that detect the changing pattern of infrared radiations emitted by a warm body of an approaching person. This characteristic of infrared waves has been used for security purposes, particularly in military technology.

(iv) Light – optical fibers in medical uses and telephone,

The high flexibility of optical fibers makes them also ideal for use in the medical industry.

An endoscope, a medical device, is a long tube consisting of optical fibers that enable doctors to see abnormalities in organs such as the stomach intestines inside a human body.

Fig: 12.6.
Endoscopy

(v) Ultra-violet – sunbeds, fluorescent tubes, sterilization,

Very hot objects, such as the Sun, emit radiations beyond the violet end of the visible spectrum, known as ultraviolet radiations. The ultraviolet is also produced by passing an electric current through the mercury vapors in the tube.

Ultraviolet radiation is further divided into three bands in order of increasing energy UV-A type, UV-B type, and UV-C type.

Wave type	UV-A	UV-B	UV-C
Wavelength	315-399nm	280-314nm	100-279nm

In fair skin, the rays can penetrate deeper and are harmful to live cells. Excess ultraviolet exposure can result in several skin diseases.

Fig: 12.7.
Sunbed

Sunbeds: Ultraviolet lamps that emit UVA and UVB radiation are used in sunbeds for artificial tanning. It is popular in countries with long periods of limited sunlight. Under medically controlled supervision, sunbeds beautify, provide the body with vitamin D, and treat certain skin conditions.

Fluorescent: When absorbed in ultraviolet, some materials convert their energy into light and glow. This phenomenon is called fluorescence.

Fig: 12.8.
Fluorescent watch dial

Do You Know!

- Many invisible things to the human eye become visible under UV light.
- Ultraviolet rays are visible to bees.
- Ultraviolet means beyond white light.
- UV light can damage the human skin

In fluorescent lamps, the inside of the tube is coated with white powder (fluoresce), which gives off light when it absorbs ultraviolet. They are commonly used in lighting houses, shops, and offices for decorating purposes.

Sterilization; as ultraviolet kills harmful bacteria, strong UVB and UVC radiations are used to sterilize food and medical equipment in hospitals.

(vi) Applications of X -rays

X-rays are produced when fast-moving electrons lose their energy quickly. For example, in an x-ray tube, the radiation is given off when a beam of fast-moving electrons hits the metal target.

The long-wavelength or low-frequency x-rays are highly penetrating that can pass through flesh but not bones. In the medical imaging field, radiologists use low-frequency x-rays to produce the x-ray images to diagnose the fracture in the bones or even tooth decay, tumors, and abnormal masses inside the body.

Fig: 12.9.
CT Scan

Computed Tomography (CT) scan is a computational diagnostic tool for detecting diseases and injuries. It uses a series of low-frequency X-rays and a computer to produce a 3D image of soft tissues and bones.

Radiation Therapy is a cancer treatment that uses controlled doses of high-frequency x-rays to kill cancerous cells and shrink tumors.

Fig: 12.10.
Radio therapy

Industrial radiography is a technique of inspecting materials to detect inside defects by using high-frequency X-rays. In this method, a beam of x-rays points at the tested item. A detector is aligned with the beam on the other side of the item. The detector records x-rays that pass through the material. The thicker the material, the fewer x-rays can pass through. More rays move through that region because the material is thinner with a crack or flaw. The detector computes a picture from the rays that pass through, which shows cracks or flaws in that material.

Do You Know!

Gamma rays have wavelength of less than 100 picometer (pm) Gamma rays have the greatest energy.

(vii) Applications of Gamma rays

Gamma rays come from radioactive materials. They are produced when the nuclei of unstable atoms decay into a

stable nucleus or lose energy. They tend to have high energy than x-rays.

Gamma rays are used to treat cancer. These high-energy rays are directed at the cancerous tumor to kill cancer cells in oncology.

The Gamma Knife Radiosurgery is a medical procedure that uses gamma rays to destroy small tumors in the brain with less damage to surrounding cells.

Positron Emission Tomography (PET) is a functional medical imaging method. In a PET scan, a short-lived positron-emitting radioactive sampling taken suitable for a particular function (e.g., brain function) is injected into the body. Radiated positrons quickly fuse with nearby electrons and lead to two gamma rays of 511-keV traveling in opposite directions. After detecting the gamma rays, a computer generates an image that highlights the location of the biological process being examined.

Gamma rays are highly penetrating and can pass through metals; because of their extreme power, gamma rays used to radiograph holes and defects in metal castings and other structural parts.

Fig: 12.11
Gamma Knife

Do You Know!

X- rays are shorter in wave length than UV rays and longer than gamma rays wavelength range (0.01 – 10 nm)

Do You Know!

PET scans are used to trace imaging of brain tumors

SELF-ASSESSMENT QUESTIONS:

Q1: State health risks associated with high energy components of electromagnetic radiations?

Q2: What is the advantage of optical fibers in telecommunication over copper cables?

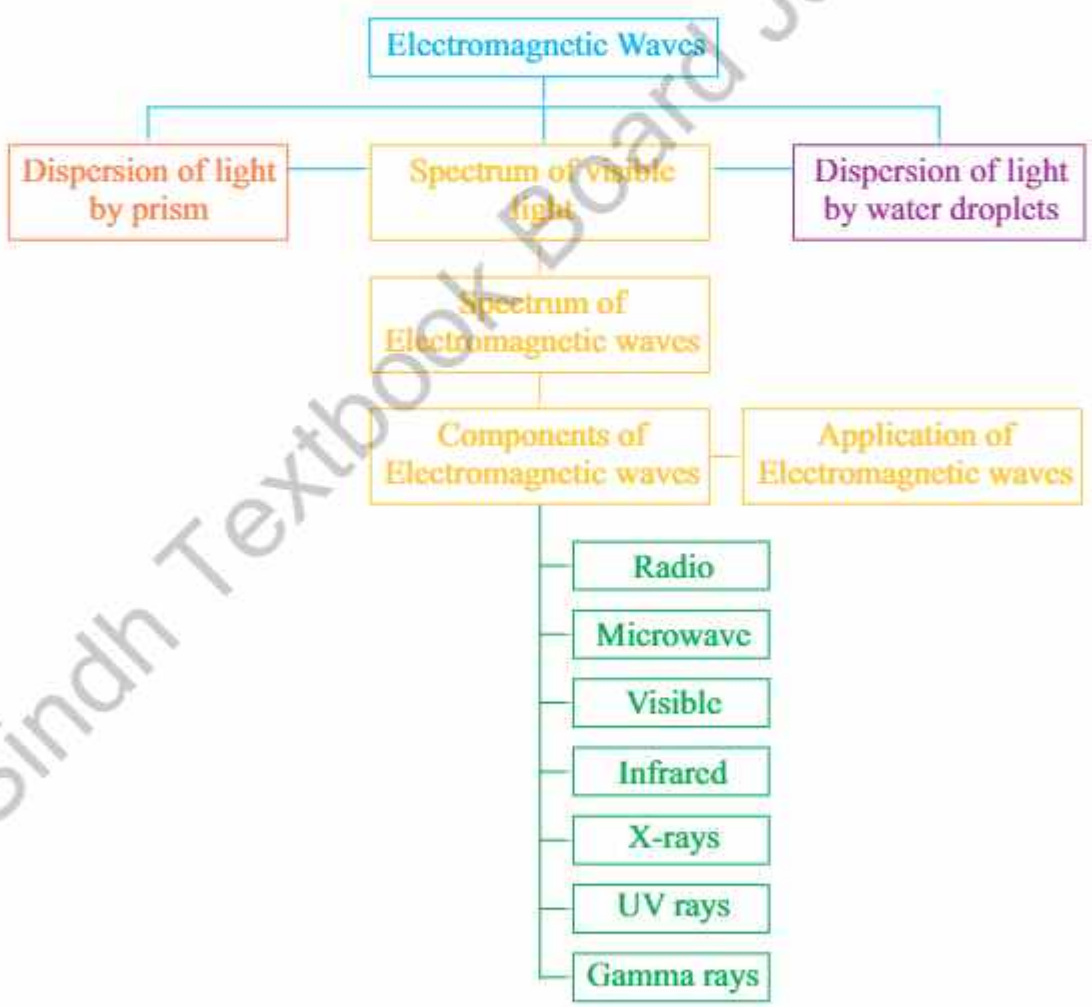
Q3: State the role played by gamma radiations in radiosurgery.

SUMMARY

- A prism is a transparent block of glass that produces dispersion.
- The prism refracts the narrow beam of white light that cause the spectrum of colors.
- Dispersion of white light is splitting white light into its constituent colors.
- Every wavelength of light changes speed and direction accordingly when it passes through another transparent medium.
- Dispersion of white light in a water droplet is the combination and total internal reflection.
- The electromagnetic spectrum is the range of all electromagnetic waves or radiations.
- The electromagnetic waves are transverse; oscillations of their electric and magnetic fields are perpendicular to energy transfer.
- All electromagnetic waves travel through a vacuum at the same speed of $c = 3 \times 10^8\ m.s^{-1}$.
- The electromagnetic waves travel through a transparent medium; however, they slow down when traveling through other denser mediums.
- The electromagnetic waves obey the laws of reflection, refraction, and diffraction.
- The electromagnetic spectrum, from the longest to shortest wavelength, includes all radio waves, microwaves, infrared radiation, visible light, ultraviolet radiation, X-rays, and gamma rays.
- Radio waves have the longest wavelengths in the electromagnetic spectrum.
- Microwaves have wavelengths in the micrometer range.
- Infra-red is used in wireless remote controllers.
- Intruder alarms use infrared radiations that detect the changing pattern emitted by a warm body at night.
- The white light is a small portion of the electromagnetic spectrum that is only visible to our eyes.
- Optical fibers work on the principle of total internal reflection.
- Optical fibers are widely used in communications technology.
- An endoscope is a medical device of optical fibers that enables doctors to see abnormalities in organs inside a human body.

- Ultraviolet radiations are commonly used in sun beads, fluorescence, and sterilization.
- X-rays are used in CT scans for medical imaging and radiotherapy to treat cancer.
- The cyberknife uses gamma rays in radiosu cancerous cells.
- PET uses the gamma rays in medical imaging to produce functional three-dimensional images of abnormal tissues or tumors.

CONCEPT MAP



Section (A) Multiple Choice Questions (MCQs)

Choose the correct answer from the following choices:

1. The waves that have maximum penetrating power to treat tumors are;
   a) Ultraviolet radiation b) Microwaves
   c) Gamma-rays d) Radio waves

2. The electromagnetic rays used in radiotherapy to destroy cancer cells are;
   a) Infrared rays b) Visible rays
   c) X - rays d) Ultraviolet rays

3. The Velocity of light in a diamond is
   (whereas the refractive index of a diamond with respect to vacuum is 2.5)
   a) 1.2×10^{8} m/s b) 5×10^{8} m/s
   c) 1.2×10^{10} m/s d) 2.5×10^{8} m/s

4. The group containing only electromagnetic waves is;
   a) Light waves, Radio waves, Microwaves
   b) Light waves, Radio waves, Sound waves
   c) Light waves, Sound waves, Microwaves
   d) Radio waves, Sound waves, Microwaves

5. The list that shows electromagnetic waves in order of an increasing wavelength is;
   a) Microwaves, X-rays, Gamma-rays
   b) Microwaves, Gamma-rays, X-rays
   c) X-rays, gamma-rays, Microwaves
   d) Gamma-rays, X-rays, Microwaves

6. The type of electromagnetic wave used in security scanners at night is;
   a) Infra-red b) Microwaves
   c) Radio waves d) X-ray

7. A narrow beam of white light passes from air into the glass and is refracted. The wave characteristic remains unchanged in its;
   a) Direction b) Frequency
   c) Speed d) Wavelength

8. The type of waves that are used in the television remote controllers;
   a) Radio waves b) Infra-red waves
   c) Ultra-violet waves d) Visible light

9. The color that is least deviated by a prism;
   a) Violet ray b) Green ray
   c) Red ray d) Yellow ray

10. The optical phenomenon in which the splitting of white light into seven distinct colors occur is called;
   a) Refraction b) Reflection
   c) Dispersion d) Diffraction

Section (B) Structured Questions

1. **a)** Define dispersion of light.
   b) Describe the dispersion of light when passing through a glass prism.

2. **a)** Explain how the rainbow is produced on a rainy day?
   b) Explain how the colors are related to distinct frequency or wavelength?

3. **a)** What are electromagnetic waves?
   b) List the main components of the electromagnetic spectrum in decreasing order of their wavelengths.
   c) Ultraviolet rays have a higher frequency than radio waves. Can UV rays travel faster in a vacuum?

4. Compare the properties of ultraviolet rays and radio signals.
   a) Which one travels at a faster speed?
   b) Which wave has a greater frequency?
   c) Which wave has a greater wavelength?

5. **a)** What are the main sources of radio waves?
   b) What is the main advantage of using radio waves in communication?

6. Why are microwaves preferred in satellite communication?

7. **a)** What type of radiation is commonly used in remote controllers for household appliances?
   b) How do the molecules emit infrared radiations?
   c) How intruder alarms help security personnel visualize the thermal images

8. **a)** On what principle do optical fibers work?
   b) Reference the daily life applications of optical fibers in;
   i. telecommunication
   ii. medical industry?

9. **a)** Exposure to sunlight can damage the skin. Exposure to sunlight does not damage the skin. State the possible reason.
   b) Why are ultraviolet rays used under medically supervised control in sunbeds?
10. **a)** Explain fluorescence.
    b) Describe sterilization.
11. X-rays are used to detect cracks in metals. Explain how?
12. **a)** Where do gamma rays come from?
    b) How are gamma radiations used in radiosurgery for destroying cancerous cells?
    c) Explain the applications of gamma rays used in hospitals for medical imaging.

Section (C) Numericals

1. Electromagnetic radiation having a 15.0−μm wavelength is classified as infrared radiation. What is its frequency? Given that the speed of light is 3×10^8 m/s. **(2×10^{13}Hz)**
2. What is the frequency of the 193-nm ultraviolet radiation used in laser eye surgery? **(1.55×10^{15}Hz)**
3. Calculate the wavelength of 100-MHz radio waves used in an MRI unit? **(3m)**
4. The distance from earth to sun is 1.49×10^{11} meters. How long a radio pulse radiated from the sun takes to reach on the earth? **(496.67 sec)**
5. Distances in space are often measured in units of light-years, the distance light travels in one year. Find the distance in kilometers in a light-year? **(9.33×10^{12}Km)**
6. What is the frequency of green light with a wavelength of 5.5×10^7m? **(5.45Hz, 5.45×10^{14}Hz)**
7. A typical household microwave oven operates at a frequency of 2.45-GHz. What is the wavelength of this radiation? **(0.1224m or 122.4mm)**