Electromagnetic Waves

INTRODUCTION & HISTORICAL DEVELOPMENTS

Since a changing magnetic field creates an electric field so James Clerk Maxwell proposed that a time-varying electric field also generates a magnetic field.

Ampere's Circuital Law and Discrepancy

- While applying Ampere's Circuital Law to find the magnetic field outside a capacitor connected to a time-varying current, Maxwell discovered an inconsistency.
- Maxwell introduced the concept of "displacement current" to resolve this inconsistency.

Maxwell's Equations

- Maxwell formulated a set of equations, known as Maxwell's equations, which describe the relationship between electric and magnetic fields, as well as their sources (charge and current densities).
- These equations mathematically express the fundamental laws of electromagnetism.

Emergence of Electromagnetic Waves

- Maxwell's equations predicted the existence of electromagnetic waves.
- Electromagnetic waves are time-varying electric and magnetic fields that propagate through space.
- The speed of electromagnetic waves, as predicted by Maxwell's equations, is very close to the speed of light (approximately 3×10^8 m/s), as confirmed by optical measurements.
- This discovery led to the conclusion that light is an electromagnetic wave.

Experimental Confirmation and Technological Impact

- In 1885, Hertz experimentally demonstrated the existence of electromagnetic waves.
- Marconi and others later utilized electromagnetic waves for communication technology, revolutionizing communication.

MAXWELL'S DISPLACEMENT CURRENT

Revising Ampere's circuital law

It states that the line integral of magnetic field B along any closed loop C is proportional to the current I passing through the closed loop i.e.

$$\oint \vec{B}.\vec{dl} = \mu_o I \qquad \text{......(i)}$$

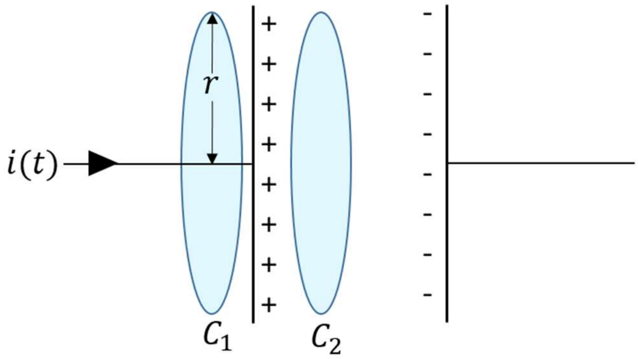
Maxwell showed that the equation (i) is logically inconsistent.

Proving logical inconsistency in Maxwell's law

Consider a parallel plate capacitor being charged by a battery as shown. As the charging continues, a current I flows through the connecting wires, which changes with time. This current produces a magnetic field around the capacitor. Consider two planar loops C_1 and C_2, C_1 just left of capacitor and C_2 in between the capacitor plates, with their planes parallel to these plates.

Now the current I flows across the area bounded by the loop C_1 because connecting wires passes through it. Hence from Ampere's law, we have

$$\oint_{C_1} \vec{B}.\vec{dl} = \mu_o I \qquad \text{.... (ii)}$$



But the area bounded by C_2 lies in the region between the capacitor plates, so no current flows across it.

$$\therefore \oint_{C_2} \vec{B}.\vec{dl} = 0 \qquad \text{.... (iii)}$$

Imagine the loops C_1 and C_2 to be infinitesimally close to each other, then we must have

$$\oint_{C_1} \vec{B}.\vec{dl} = \oint_{C_2} \vec{B}.\vec{dl} \qquad \text{.... (iv)}$$

This result is inconsistent with the equations (ii) and (iii). So, need for modifying Ampere's law was felt by Maxwell.

Displacement current

- To modify Ampere's law, Maxwell followed a symmetry consideration.
- By Faraday's law, a changing magnetic field induces an electric field, hence a changing electric field must induce a magnetic field.
- As currents are usual sources of magnetic fields, a changing electric field must be associated with a current.
- Maxwell called it displacement current to distinguish it from usual conduction current caused by drift of electrons.

Displacement current is that current which comes into existence, in addition to the conduction current, whenever the electric field and hence the electric flux changes with time.

Displacement current (I_d) is given by

$$\boxed{I_d = \varepsilon_o \frac{d\varphi_E}{dt}}$$

Where φ_E is the electric flux across the loop.

- Unlike the conduction current, the displacement current exists whenever the electric field and hence the electric flux is changing with time.
- Thus, the source of magnetic field is not just the conduction current due to flowing charges, but also time-varying electric field.
- Hence the total current I is the sum of conduction current and displacement current.

Therefore, total current across the loop = $I_c + I_d = I_c + \frac{d\varphi_E}{dt}$ ...(v)

Hence, **modified form of Ampere's law is**

$$\boxed{\oint \vec{B}.\vec{dl} = \mu_o \left[I_c + \varepsilon_o \frac{d\varphi_E}{dt} \right]} \quad \text{.... (vi)}$$

If A is the area of the capacitor plates and q be the charge on the plates at any instant t during the charging process, then the electric field in the gap will be

$$E = \frac{q}{\varepsilon_o A}$$

$$\text{or } EA = \frac{q}{\varepsilon_o}$$

$$\text{or } \varphi_E = \frac{q}{\varepsilon_o}$$

$$\therefore \oint_{C_2} \vec{B}.\vec{dl} = \mu_o \varepsilon_o \frac{d}{dt}\left(\frac{q}{\varepsilon_o}\right) = \mu_o \frac{dq}{dt}$$

$$\text{or } \oint_{C_2} \vec{B}.\vec{dl} = \mu_o I$$

This agrees with equation (ii) and proves Ampere's modified law.

- The concept of displacement current leads to more symmetrical laws of electricity and magnetism.
- Faraday's law of electromagnetic induction states that a changing magnetic field induces an electric field.

- Conversely, a changing electric field induces a magnetic field, as a consequence of the displacement current being a source of magnetic field.
- Time-dependent electric and magnetic fields are interrelated.
- Faraday's law and Ampere-Maxwell law quantitatively express this symmetry.
- This symmetry leads to the existence of electromagnetic waves.

MAXWELL'S EQUATIONS

Maxwell found that all the basic principles of electromagnetism can be formulated in terms of four fundamental equations called Maxwell's equations. These are

1. **Gauss law in electrostatics :** $\oint_S \vec{E}.\overrightarrow{ds} = \frac{q}{\varepsilon_o}$
2. **Gauss law in magnetism :** $\oint_S \vec{B}.\overrightarrow{ds} = 0$
3. **Faraday's laws of electromagnetic induction :** $\oint_C \vec{E}.\vec{dl} = -\frac{d\varphi_B}{dt}$
4. **Modified Ampere's law** : $\oint \vec{B}.\vec{dl} = \mu_o \left[I_c + \varepsilon_o \frac{d\varphi_E}{dt} \right]$

ELECTROMAGNETIC WAVES AND THEIR SOURCES

Sources of Electromagnetic Waves:

- Stationary charges and charges in uniform motion (steady currents) do not produce electromagnetic waves.
- Stationary charges generate only electrostatic fields.
- Steady currents generate magnetic fields, but these fields do not vary with time.

Acceleration of Charges and Electromagnetic Waves:

- Maxwell's theory reveals that accelerated charges emit electromagnetic waves.
- Accelerated charges, such as oscillating charges, produce oscillating electric fields.
- Oscillating electric fields generate oscillating magnetic fields, creating a continuous cycle.
- The resulting oscillating electric and magnetic fields regenerate each other, forming the electromagnetic wave.
- The frequency of the electromagnetic wave matches the frequency of the charge's oscillation.

- Energy carried by the wave is derived from the energy of the source, the accelerated charge.

Challenges in Testing the Nature of Light:

- Initially, it seemed feasible to test whether light is an electromagnetic wave by creating an alternating current (ac) circuit with a frequency matching visible light (e.g., yellow light).
- However, the frequency of visible light, like yellow light, is extremely high (about 6×10^{14} Hz).
- Modern electronic circuits can produce frequencies up to about 10^{11} Hz, far below the frequency of visible light.
- Therefore, experimental demonstrations of electromagnetic waves had to occur in the low-frequency region, like radio waves, as demonstrated in Hertz's experiment in 1887.

Contributions to the Study of Electromagnetic Waves:

- Hertz's successful experimental test of Maxwell's theory led to significant developments in this field.
- Seven years later, Jagdish Chandra Bose in Calcutta (now Kolkata) produced and observed electromagnetic waves with much shorter wavelengths (25 mm to 5 mm) in a laboratory setting.
- Guglielmo Marconi in Italy followed Hertz's work and achieved the transmission of electromagnetic waves over long distances, marking the beginning of communication using electromagnetic waves.

Nature of Electromagnetic Waves

Characteristics of Electromagnetic Waves:

- Electromagnetic waves exhibit specific characteristics based on Maxwell's equations.
- Electric and magnetic fields in an electromagnetic wave are perpendicular to each other and to the direction of wave propagation.

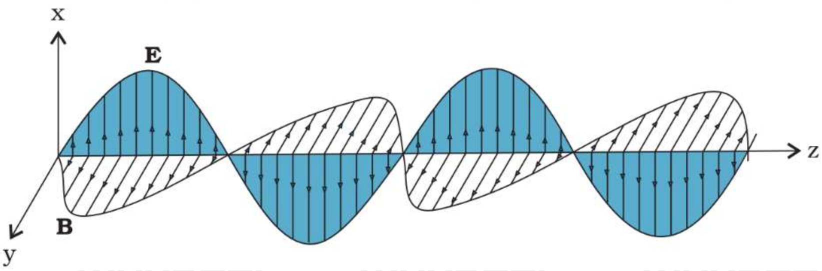
Perpendicular Fields:

- In an electromagnetic wave, the electric field (E) and magnetic field (B) are always at right angles to each other.
- This relationship holds true for all electromagnetic waves.

Figure show a typical example of a plane electromagnetic wave propagating along the z direction (the fields are shown as a function of the z coordinate, at a given time t).

The electric field E_x is along the x-axis, and varies sinusoidally with z, at a given time. The magnetic field B_y is along the y-axis, and again varies sinusoidally with z. The electric and magnetic fields E_x and B_y are perpendicular to each other, and to the direction z of propagation. We can write E_x and B_y as follows:

$$E_x = E_o \sin(kz - \omega t)$$
$$B_y = B_o \sin(kz - \omega t)$$



- ✓ Here k is related to the wave length λ of the wave by the usual equation

  $$k = \frac{2\pi}{\lambda}$$

- ✓ ω is the angular frequency.
- ✓ k is the magnitude of the wave vector (or propagation vector)
- ✓ $\vec{k}$ and its direction describes the direction of propagation of the wave.
- ✓ The speed of propagation of the wave is $\left(\frac{\omega}{k}\right)$.
- ✓ From above discussion, it can be proved that $\boxed{c = \frac{1}{\sqrt{\mu_o \varepsilon_o}}}$.
- ✓ For a medium m other than free space, we have $\boxed{c_m = \frac{1}{\sqrt{\mu_m \varepsilon_m}}}$.
- ✓ It is also seen from Maxwell's equations that the magnitude of the electric and the magnetic fields in an electromagnetic wave are related as $\boxed{B_o = \frac{E_o}{c}}$.

IMPORTANCE OF ELECTROMAGNETIC WAVES

Speed of Electromagnetic Waves in Space:

- Electromagnetic waves, like light and radio waves, travel at a certain speed in the empty space between stars and planets.
- This speed is always the same, no matter what colour of light or type of radio wave you have.
- It's super-fast, about 300,000,000 meters per second!

Why Speed Matters:

- Scientists are very sure about this speed because they've done many experiments to check it.
- It's so reliable that we use it to measure things. It helps us define a standard length.

Why Electromagnetic Waves Are Important:

- Electromagnetic waves are incredibly useful in our technology.
- They can carry messages for us, like the signals from radio and TV stations that bring us news and entertainment.
- Light, a kind of electromagnetic wave, brings energy from the sun to our planet. This energy is what makes life possible on Earth.

ELECTROMAGNETIC SPECTRUM

- The classification of EM waves according to frequency is the electromagnetic spectrum. There is no sharp division between one kind of wave and the next.
- The classification is based roughly on how the waves are produced and/or detected.
- We briefly describe these different types of electromagnetic waves, in order of decreasing wavelengths.

Radio Waves

Production of Radio Waves:

- Radio waves are generated by the accelerated movement of electric charges in conducting wires.
- They result from the back-and-forth motion of charges, such as electrons, in these wires.

Applications of Radio Waves:

- Radio waves are widely utilized in communication systems, particularly in radio and television.
- They play a crucial role in transmitting audio and visual signals over long distances.

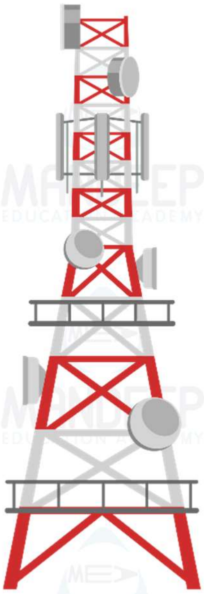
Frequency Range of Radio Waves:

- Radio waves have a broad range of frequencies.
- Typically, radio waves span from 500 kHz (kilohertz) to about 1000 MHz (megahertz).

Different Bands of Radio Waves:

- The AM (amplitude modulated) band covers frequencies from 530 kHz to 1710 kHz.
- Shortwave bands use higher frequencies, extending up to 54 MHz.
- TV waves occupy the range from 54 MHz to 890 MHz.
- The FM (frequency modulated) radio band falls between 88 MHz and 108 MHz.

Use of Radio Waves in Cellular Phones:



- Cellular phones use radio waves to transmit voice communications.
- They operate in the ultrahigh frequency (UHF) band, allowing for wireless communication over short distances.

Microwaves

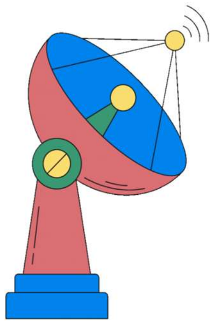
Characteristics of Microwaves:

- Microwaves are a type of electromagnetic wave with shorter wavelengths than radio waves.
- They have frequencies in the gigahertz (GHz) range, which means they have a very high frequency.

Production of Microwaves:

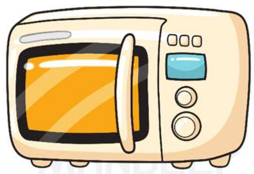
- Microwaves are produced using special vacuum tubes, such as klystrons, magnetrons, and Gunn diodes.
- These devices generate and amplify microwaves, making them suitable for various applications.

Applications of Microwaves:



- Microwaves have several practical applications:
    - **Radar Systems:** Microwaves are used in radar systems for aircraft navigation, providing precise and rapid detection of objects in the air.

    - **Speed Guns:** Radar serves as the basis for speed guns, which are used to measure the speed of fast-moving objects like balls, tennis serves, and automobiles.
    - **Microwave Ovens:** Perhaps the most familiar domestic application of microwaves is in microwave ovens.



Microwave Ovens:

- In microwave ovens, the microwaves are emitted at a frequency that matches the resonant frequency of water molecules.
- When the microwaves interact with water molecules, they efficiently transfer energy to the molecules.

- This energy transfer leads to the rapid movement of water molecules, raising the temperature of any food containing water.
- Microwave ovens are highly efficient at heating food quickly due to this resonant interaction with water molecules.

Infrared Waves

Production of Infrared Waves:

- Infrared waves are generated by hot objects and molecules.
- They are found at the low-frequency or long-wavelength end of the visible spectrum.

Infrared Waves as Heat Waves:

- Infrared waves are often referred to as "heat waves" because they have the ability to generate heat.
- Most materials, including water molecules, readily absorb infrared waves.
- When absorbed, these waves increase the thermal motion of molecules, effectively raising their temperature and warming their surroundings.

Applications of Infrared Waves:

- Infrared waves have several important applications:
    - **Physical Therapy:** Infrared lamps are used in physical therapy to provide targeted heat therapy for various medical conditions.
    - **Greenhouse Effect:** Infrared radiation plays a vital role in the Earth's climate through the greenhouse effect. Incoming visible light is absorbed by the Earth's surface and re-emitted as longer-wavelength infrared radiation. Greenhouse gases like carbon dioxide and water vapor trap some of this radiation, helping to maintain the Earth's average temperature.

    - **Earth Observations:** Infrared detectors are utilized in Earth satellites, both for military purposes and for monitoring crop growth.
    - **Consumer Electronics:** Electronic devices like semiconductor light-emitting diodes emit infrared waves. These are widely used in remote controls for household electronic systems, such as TVs, video recorders, and hi-fi systems.

Visible Light

Introduction to Visible Light:

- Visible light is the most familiar form of electromagnetic waves.
- It's the part of the electromagnetic spectrum that our eyes can detect.
- Humans see visible light, and it provides us with information about the world.

Frequency and Wavelength of Visible Light:

- Visible light spans from about 4×10^{14} Hz to about 7×10^{14} Hz on the frequency scale.
- It corresponds to a wavelength range of about 700 nanometers (nm) to 400 nm on the wavelength scale.

Our Sensitivity to Visible Light:

- Our eyes are sensitive to this specific range of wavelengths, allowing us to see the world around us.
- Different animals have different sensitivities to various parts of the electromagnetic spectrum.

- For example, snakes can detect infrared waves, which are outside our visible range.
- Many insects can see ultraviolet light, which is also beyond our visible range.

Ultraviolet (UV) Rays

Description of Ultraviolet Light:

- Ultraviolet (UV) rays are a type of electromagnetic radiation.
- They have shorter wavelengths, ranging from about 400 nanometers (nm) to 0.6 nm.

Sources of Ultraviolet Radiation:

- UV radiation is produced by specific lamps and very hot objects.
- The sun is a significant natural source of UV light, but most of it is absorbed in the ozone layer in the Earth's atmosphere, located around 40 to 50 kilometers above the surface.

Effects of UV Radiation:

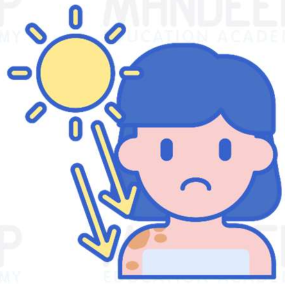
- UV light has both beneficial and harmful effects on humans.

- Exposure to UV radiation stimulates the production of melanin, causing the skin to tan.
- However, excessive UV exposure can lead to sunburn and increase the risk of skin cancer.

Interaction with Glass:

- Ordinary glass effectively absorbs UV radiation, so UV rays do not pass through glass windows.
- This means that you cannot get a tan or sunburn through glass windows.

Protective Measures:

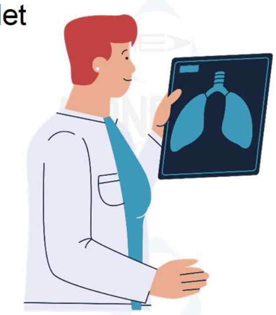


- Welders wear special goggles or face masks with UV-resistant glass windows to shield their eyes from the intense UV produced during welding.
- Due to its short wavelengths, UV radiation can be focused into narrow beams for precise applications like LASIK eye surgery.
- UV lamps are used in water purifiers to kill germs and make water safe to drink.

Importance of the Ozone Layer:

- The ozone layer in the Earth's atmosphere plays a crucial protective role by absorbing and blocking a significant portion of harmful UV radiation.
- The depletion of the ozone layer, primarily due to substances like chlorofluorocarbons (CFCs), is a global environmental concern.

X-rays



- X-rays are a part of the electromagnetic spectrum, lying beyond the ultraviolet (UV) region.
- They have wavelengths ranging from about 10 nanometers (nm) to 0.0001 nm.
- X-rays are commonly known for their medical applications.

Generation of X-rays:

- One common method to generate X-rays is by bombarding a metal target with high-energy electrons.
- X-rays are valuable in medicine for diagnostic purposes and for treating certain types of cancer.
- However, it's crucial to use X-rays cautiously because they can damage living tissues and organisms.

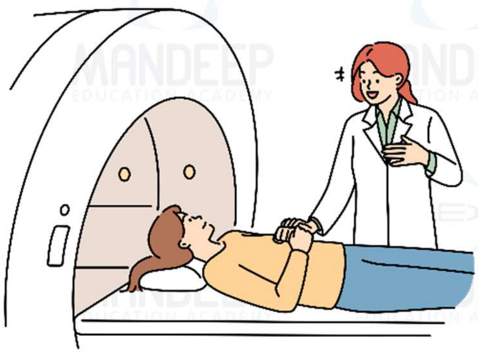
- Careful measures are taken to avoid unnecessary or excessive exposure to X-rays in medical procedures.

Gamma Rays

- Gamma rays are another type of electromagnetic radiation that lies in the upper-frequency range of the spectrum.
- They have extremely short wavelengths, from about 10^{-8} m to less than 10^{-13} m.

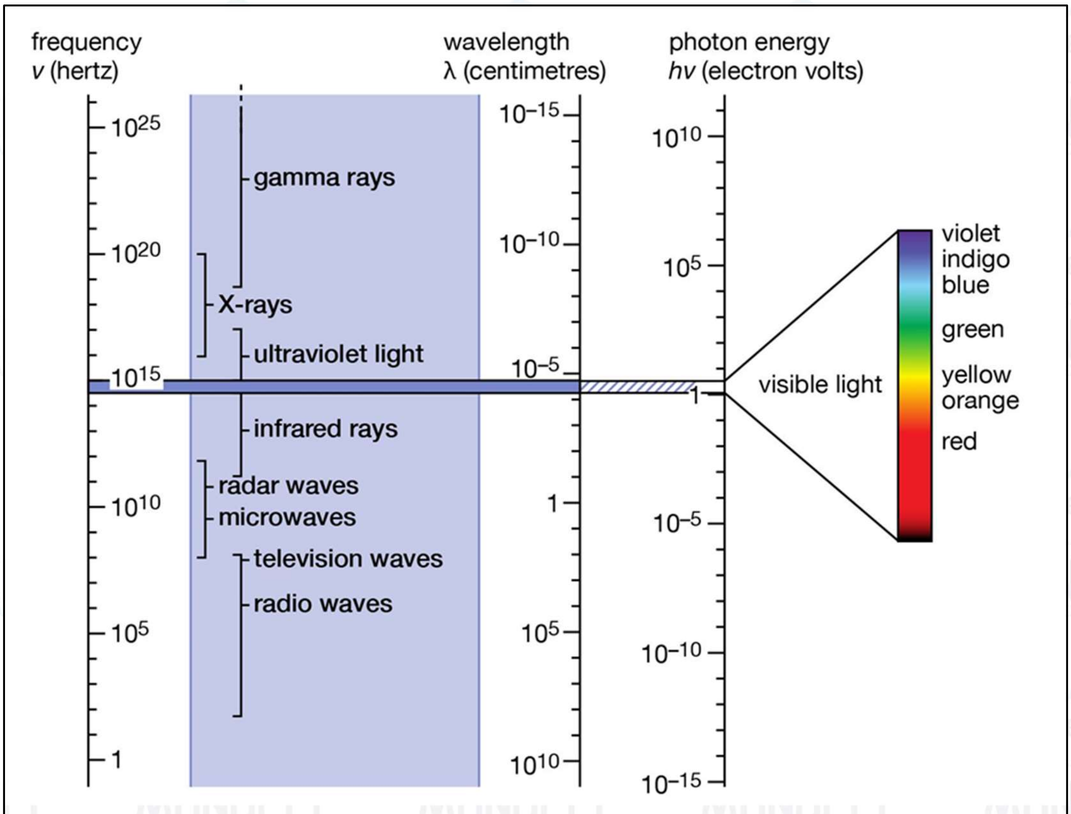
Sources of Gamma Rays:

- Gamma rays are produced in nuclear reactions, including those in nuclear power plants and during nuclear decay processes.
- Radioactive nuclei also emit gamma rays.



Medical Applications of Gamma Rays:

- Gamma rays are used in medicine to destroy cancer cells.
- Radiation therapy involving gamma rays is a common approach for cancer treatment.



Electromagnetic spectrum