Unit-5 Electromagnetic Waves

1 Electromagnetic Waves m.imp:

A wave originated by changing electric field and magnetic field is called electromagnetic waves. These waves are transverse in nature and propagate in a direction perpendicular to both electric and magnetic field. Electric and magnetic field are also perpendicular to each other.

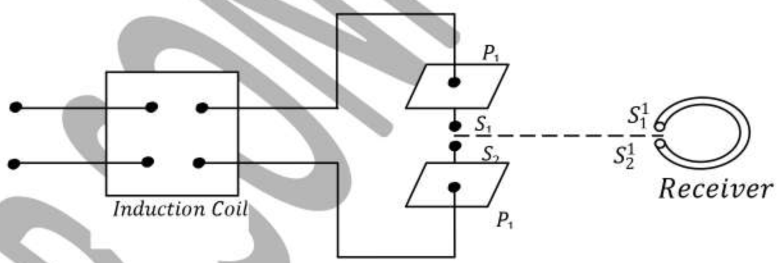
These waves do not require any material medium for their propagation.

2 Hertz Demonstration of Electromagnetic Waves:

In 1887, a German Scientist Hertz demonstrated an experiment for production of electromagnetic waves using an oscillatory circuit.

He used two large metallic plates P_1 and P_2 connected input to an induction coil.

The two metallic spheres separated by a small air gap are connected to the metallic plates, which acts as a capacitor of capacitance C.



When input is supplied then spark produces between metallic plates which produce electromagnetic waves of frequency $v = \frac{1}{2\pi\sqrt{LC}}$

This frequency can be observed by receiver

✓ *The frequency produced by Hertz experiment was small, later J.C. Bose and Marconi obtained large frequency electromagnetic waves.*

3 Characteristics/Properties of Electromagnetic Wave m. imp:

- These waves do not require any material medium for their propagation.
- These waves are transverse in Nature.
- The electric field $\vec{E}$ and magnetic field which produces electromagnetic waves are ⊥ to each other and are also ⊥ to direction of propagation of light.
- The electromagnetic waves travel with velocity of light in space.
- The energy densities of electromagnetic waves of electric field and magnetic field are equal.
- the velocity of electromagnetic waves in medium is $v = \frac{1}{\sqrt{\mu\varepsilon}}$

- An electric dipole is a basic source of electromagnetic waves.
- Electromagnetic waves transport energy. *The rate of energy transported of electromagnetic waves per unit area is represented by a quantity called* **pointing vector($\vec{S}$).** i.e $\vec{S} = \frac{1}{\mu_0}(\vec{E} \times \vec{B})$

  Unit: $watt m^{-2}$
- *The electric field vector $\vec{E}$ is responsible for the optical effect of light. There electric field vector are called* ***light vector.***
- Electromagnetic waves do not deflect by electric and magnetic field.
- Electromagnetic waves obey principle of superposition. They show the properties of reflection, refraction, interference, diffraction on and polarization.
- When electromagnetic travel from one medium to another medium then its wavelength changes but frequency (inherent property) remains constant.
- The magnitude of propagation vector $\hat{K}$ of electromagnetic waves can be given as

$$K = \frac{\omega}{c} = \frac{2\pi}{\lambda}$$

4 Maxwell's concept of Electromagnetism or Displacement Current[m.imp]:

According to Maxwell, a changing magnetic field induces an electric field (faradays laws of electromagnetic induction) and hence a changing electric field must induced magnetic field.

As the electric field between two parallel plates capacitors can be given by

$$E = \frac{\sigma}{\varepsilon_0} = \frac{q}{A\varepsilon_0}$$

Now differentiating both sides we get $dE = \frac{dq}{A\varepsilon_0} = \frac{Idt}{A\varepsilon_0}$ $\quad \left(\because \; I = \frac{dq}{dt}\right)$

Or $$\frac{dE}{dt} = \frac{I}{A\varepsilon_0}$$

Or $$I = \varepsilon_0 \frac{d(EA)}{dt}$$

Or $$I = \frac{\varepsilon_0 d\phi_E}{dt} \qquad \left(\because \; \phi = \vec{E} \cdot \vec{A}\right)$$

Where ϕ_E is the electric flux and I is the current due to change in electric flux between two plates of a capacitor, this current is called *displacement current*

$$I_d = \frac{\mathcal{E}_0 d\phi_E}{dt}$$

Now as we know conduction current due to flow of charges in a conductor and are denoted by I_c

So total current $\quad I = I_c + I_d$

So from Ampere circuital law $\quad \oint \vec{B} \cdot \vec{dl} = \mu_0 I$

We get $\quad \oint \vec{B} \cdot \vec{dl} = \mu_0 (I_c + I_d)$

Or $\quad \oint B \cdot dl = \mu_0 \left(I_c + \mathcal{E}_0 \frac{d\phi_E}{dt}\right)$

The above expression is called modified form of Ampere circuital law and known as *Ampere Maxwell circuital law.*

5 Maxwell's Equations:

The Maxwell equations give the basic laws of electromagnetic. These equations are given below

(i) $\oint B \cdot dl = \mu_0 \left(I_c + \mathcal{E}_0 \frac{d\phi_E}{dt}\right)$ This eq. is known as *Ampere Maxwell Circuital Law*.

(ii) $\oint \vec{E} \cdot \vec{dS} = \frac{q}{\mathcal{E}_0}$ this eq. is known as *Gauss's theorem in electrostatics*

(iii) $\oint \vec{B} \cdot \vec{dS} = 0$ This eq. known as *Gauss's law in magnetism*.

(iv) $\oint B \cdot dl = \frac{-d\phi_B}{dt}$ This eq. is known as faradays laws in *electromagnetic induction.*

6 Continuity of current[m.imp]:

The sum of conduction current and displacement current $(I_c + I_d)$ is continuous along any closed path, although the individual conduction current (I_c) and displacement current (I_d) may not be continuous.

As $\quad I = I_c + I_d = I_c + E_0 \frac{d\phi_E}{dt} = \frac{dq}{dt}$

7 Electromagnetic Spectrum m.imp:

The whole orderly range of frequencies and wavelengths of the electromagnetic waves is known as the electromagnetic spectrum.The electromagnetic spectrum consists of the following waves.

Sr. No.	***Names***	***Frequency***	***Wavelength***	***Production***	***Detection***	***Uses***
1	Radio Waves	10^4 to 10^8 Hz (Lowest Frequency)	>0.1m or 600m to 0.1m (Highest λ)	By Oscillating e^- in LC oscillator	Receiver aerials	*In Radio and T.V.*
2	Micro Waves	10^9 to 10^{12} Hz	0.1m to 1 mm	Klystron Valve, Magnetron Valve.	Point Contact Diode	*(a) In radar communication.* *(b) Analyzing atomic and molecular structures* *(c) For cooking food.*
3	Infrared Waves	10^{11} to 5×10^{14} Hz	1mm to 700 nm	Vibrating of atoms and molecules.	Bolometer Infrared photographic plate	*(a) These rays can pass through the haze, fog and mist, so these rays are used in night vision.* *(b) These rays are used to keep green houses warm.* *(c) Infrared rays from sun keep earth warmed.* *(d) In revealing secret writing on walls.* *(e) To treat muscular pain.*
4	Visible Light	4×10^{14} to 7×10^{14} Hz	700 nm to 400 nm	Electron emits visible light when jumps from excited state to ground level.	Human eye, Photocells, Photographic film	*(a) Vision process is possible due to this* *(b) For chemical RK^n*
5	Ultra Violet Rays	10^{16} to 10^{17} Hz	400nm to 1nm	Due to e^- moving in inner shells from one level to another level.	Photocells, Photographic film.	*(a) To preserve food and making water free from bacteria's.* *(b) For sterilizing the surgical instruments.* *(c) To study the structure of molecules.* *(d) In detecting individual writing, forged documents and finger prints.*
6	X-Ray	10^{16} to 10^{19} Hz	1nm to 10^{-3}nm	From inner shell electrons.	Photographic Film, Geiger tube, ionization chamber	*(a) Penetrating matter, ionize gases, cause fluorescences, photo emission from metals, for study crystal lattice by diffraction etc.* *(b) For medical diagnostic.* *(c) In radio therapy to detect deflect.* *(d) By detective agencies to detect gold, silver diamond.*
7	γ-Ray	10^{18} to 10^{22} Hz (Highest Frequency)	$<10^{-3}$ nm (Lowest Wavelength)	Radioactive decay of the nucleus.	Photographic film, Geiger tube, Ionization Chamber	*(a) To study structure of nucleus.* (b) Medical treatment etc

1: In a plane electromagnetic wave, the electric field oscillates sinusoidal at a frequency 2×10^{10} Hz And Amplitude 48 V/m. The amplitude of oscillating magnetic field will be:

(A) $\frac{1}{16} \times 10^{-8}$ Wb/m^2 (B) 16×10^{-8} Wb/m^2 (C) 12×10^{-7} Wb/m^2 (D) $\frac{1}{12} \times 10^{-7}$ Wb/m^2

Sol: (B) Oscillating magnetic field $B = \frac{E}{c} = \frac{48}{3 \times 10^8} = 16 \times 10^{-8}$ Wb/m^2

2: In the above problem, the wavelength of the wave will be-

Sol. Wavelength of electromagnetic wave $\lambda = \frac{c}{\nu} = \frac{3 \times 10^8}{2 \times 10^{10}} = 1.5 \times 10^{-2} = 1.5$ cm

3: What should be the height of transmitting antenna if the T.V. telecast is to cover a radius of 128 km?

Sol. Height of transmitting antenna $h = \frac{d^2}{2R_e} = \frac{(128 \times 10^3)^2}{2 \times 6.4 \times 10^6} = 1280$ m

4: The area to be covered for T.V. telecast is doubled, and then the height of transmitting antenna (T.V tower) will have to be-

Sol. The area of transmission of surrounding the T.V. tower $A = \pi d^2 = \pi(2hR_e)$ $A \propto h$

5: In an electromagnetic wave, the amplitude of electric field is 1 V/m. The frequency of wave is 5×10^{14} Hz. The wave is propagating along z-axis. The average energy density of electric field, in Joule/m^3, will be-

Sol. Average energy density is given by $u_E = \frac{1}{2}\varepsilon_0 E^2 = \frac{1}{2}\varepsilon_0 \left(\frac{E_0}{\sqrt{2}}\right)^2 = \frac{1}{4}\varepsilon_0 E_0^2$

$= \frac{1}{4} \times 8.85 \times 10^{-12} \times (1)^2 = 2.2 \times 10^{-12}$ J/m^2

6: A T.V. tower has a height of 100 m. How much population is covered by T.V. broadcast, if the average population density around the tower is 1000/km^2?

Sol. Radius of the area covered by T.V. telecast $d = \sqrt{2hR_e}$

Total population covered $= \pi d^2 \times$ population density $= 2\pi h R_e \times$ population density

$= 2 \times 3.14 \times 100 \times 6.4 \times 10^6 \times \frac{1000}{10^6} = 39.503 \times 10^5$

7: An electromagnetic radiation has energy 14.4 KeV. To which region of electromagnetic spectrum does it belong?

Sol. $\lambda = \frac{hc}{E} = \frac{6.6 \times 10^{-34} \times 3 \times 10^8}{14.4 \times 10^3 \times 1.6 \times 10^{-19}} = 0.8 \times 10^{-10}$m = 0.8 Å. This wavelength belongs to X-ray region.

SOME IMPORTANT MCQ

1. If E and B are the electric and magnetic field vectors of electromagnetic waves then the direction of propagation of electromagnetic wave is along the direction of:

(A) $\vec{E}$ (B) $\vec{B}$ **(C)** $\vec{E}\times\vec{B}$ (D) None of these

2. The electromagnetic waves do not transport:

(A) Energy **(B) charge** (C) momentum (D) information

3. A capacitor is connected in an electric circuit. When key is pressed, the current in the circuit is:

(A) Zero **(B) Maximum** (C)any transient value (D) depends on capacitor used

4. Displacement current is continuous:

(A) When electric field is changing in the circuit (B) when magnetic field is changing in the circuit

(C) In both types of fields (D) through wires and resistance only

5. The magnetic field between the plates of a capacitor when r > R is given by:

(A) $\frac{\mu_0 I_D r}{2\pi R^2}$ (B) $\frac{\mu_0 I_D}{2\pi R}$ **(C)** $\frac{\mu_0 I_D}{2\pi r}$ (D) 'kwU;

Sol. (C) According to Ampere's law, when r > R B = $\frac{\mu_0 I_D}{2\pi r}$

6. The conduction current is the same as displacement current when the source is:

(A) A.C. only **(B) D.C. only**

(C) Both A.C. and D.C. (D) Neither for A.C. nor for D.C.

7. The wave function (in S.I. units) for an electromagnetic wave is given as:

Ψ (x, t) = $10^3 \sin\pi (3 \times 10^6 x - 9 \times 10^{14} t)$ the speed of the wave as:

(A) 9×10^{14} m/s **(B) 3×10^8 m/s** (C) 3×10^{16} m/s (D) 3×10^7 m/s

Sol. (B) $c = \frac{\omega}{k} = \frac{9\times10^{14}}{3\times10^6} = 3 \times 10^8$ m/s

8. In an electromagnetic wave the average energy density is associated with:

(A) electric field only (B) magnetic field only

(C) Equally with electric and magnetic fields (D) average energy density is zero

9. In an electromagnetic wave the average energy density associated with magnetic field will be:

(A) $\frac{1}{2}LI^2$ **(B)** $\frac{B^2}{2\mu_0}$ (C) $\frac{1}{2}\mu_0 B^2$ (D) $\frac{1}{2}\frac{q}{B^2}$

10. in the above problem, the energy density associated with the electric field will be:

(A) $\frac{1}{2}CV^2$ (B) $\frac{1}{2}\frac{q^2}{C}$ (C) $\frac{1}{2}\frac{\varepsilon^2}{E}$ **(D)** $\frac{1}{2}\varepsilon_0 E^2$

11. If there were no atmosphere, the average temperature on earth surface would be:

(A) Lower (B) Higher (C) same (D) 0^{o}C

Sol. (A) The green house effect would not have been possible without atmosphere. Hence temperature would be lower.

12. In which part of earth's atmosphere is the ozone layer present?

(A) Troposphere **(B) Stratosphere** (C) Ionosphere (D) Mesosphere

13. Kenneley's Heaviside layer lies between:

(A) 50Km to 80 Km (B) 80Km to 400 Km **(C) beyond 110 Km** (D) beyond 250 Km

14. The ozone layer in earth's atmosphere is crucial for human survival because it:

(A) Has ions (B) reflects radio signals **(C) reflects ultraviolet ray** (D) reflects infra red rays

15. The frequency from 3×10^9 Hz to 3×10^{10} Hz:

(A) High frequency band **(B) Super high frequency band**

(C) Ultra high frequency band (D) High frequency band

16. The frequency from 3 to MHz is known as:

(A) Audio band **(B) Medium frequency band**

(C) Very high frequency band (D) High frequency band

17. The AM range of radio waves has frequency:

(A) Less than 30 MHz (B) More than 30 MHz

(C) Less than 20000 Hz (D) More than 20000 Hz

18. The displacement current flows in the dielectric of a capacitor

(A) Becomes zero (B) has assumed a constant value

(C) Is increasing with time (D) is decreasing with time

19. Select wrong statement from the following Electromagnetic waves:

(A) Are transverse **(B) travel with same speed in all media**

(C) travel with the speed of light (D) are produced by acceleration charge

20. The waves related to tele-communication are:

(A) Infra red (B) visible light **(C) Microwaves** (D) ultraviolet rays

21. Electromagnetic waves do not transport:

(A) Energy (B) charge (C) Momentum (D) information

22. The nature of electromagnetic wave is:

(A) Longitudinal (B) longitudinal stationary **(C) Transverse** (D) transverse stationary

23. Greenhouse effect keeps the earth surface:

(A) Cold at night (B) dusty and cold **(C) warm at night** (D) moist

24. **A plane electromagnetic wave of frequency 40 MHz travels in free space in the X-direction. At some point and at some instant, the electric field $\vec{E}$ has its maximum value of 750 N/C in Y-direction. The wavelength of the wave is:**

(A) 3.5 m (B) 5.5 m **(C) 7.5 m** (D) 9.5 m

Sol. (C) $\lambda = \frac{C}{f} = \frac{3\times10^8}{4\times10^7} = 7.5m$

25. **in the above problem, the period of the wave will be:**

(A) 2.5 μs (B) 0.25 μs **(C) 0.025 μs** (D) None of these

Sol. (C) $T = \frac{1}{f} = \frac{1}{4\times10^7} = 0.025\mu s$

26. **in Q. 40, the magnitude and direction of magnetic field will be:**

(A) 2.5 μT in X-direction (B) 2.5 μT in Y-direction **(C) 2.5 μT Z-direction** (D) none of these

Sol. (C) $B_m = \frac{E_m}{C}\ \frac{750}{3\times10^8} = 2.5\mu T$ Z-direction = 1.34 V/m

27. **in Q. 5, the energy density at a distance 3.5m from the source wills be_ (in joule/m³)**

(A) 1.73×10^{-5} (B) 1.73×10^{-6} (C) 1.73×10^{-7} **(D) 1.73×10^{-8}**

Sol. (D) Energy density at 3.5m is given by

$u = \frac{1}{2}\varepsilon_0 E_m^2 = \frac{1}{2}\times 8.85\times10^{-12}\times(62.6)^2 = 1.73\times10^{-8}$ hence the correct answer will be (D)