ELECTROMAGNETIC WAVES

BASIC CONCEPTS AND FORMULAE

1. ELECTROMAGNETIC WAVES

The wave propagating in space through electric and magnetic fields varying in space and time simultaneously are called electromagnetic waves.

2. ORIGIN

The electromagnetic waves are produced by an accelerated or decelerated charge or LC circuit. The frequency of e.m. waves is

$$\nu = \frac{1}{2\pi\sqrt{LC}}$$

3. CHARACTERISTICS OF ELECTROMAGNETIC WAVES

(i) The electromagnetic wave travel in free - space with the speed of light ($c = 3 \times 10^8$ m/s)

(ii) Electromagnetic waves are neutral, so they are not deflected by elecric and magnetic fields.

(iii) The electromagnetic waves shown properties of refraction, interfernece, diffraction and polarisation.

(iv) In electromagnetic wave the electric and magnetic fields are always in the same phase.

(v) The ratio of magnitudes of electric and magnetic field vectors in free space is constant equal to c

$$\frac{E}{B} = \frac{1}{\sqrt{\mu_0\varepsilon_0}} = c = 3\times10^8\ m/s$$

(vi) The speed of electromagnetic waves in a material medium is given by

$$\nu = \frac{1}{\sqrt{\mu\varepsilon}} = \frac{c}{\sqrt{\mu_r\varepsilon_r}} = \frac{c}{n},$$ where n is the refractive index.

(vii) In an electromagnetic wave the energy is propagated by means of electric and magnetic field vectors in the direction of propagation of wave.

(viii) In electromagnetic wave the average values of electric energy density and magnetic energy densities are equal

$$\left(\frac{1}{2}\varepsilon_0 E^2\right)_{av} = \left(\frac{B^2}{2\mu_0}\right)_{av}$$

(ix) The electric vector of electromagnetic wave is responsible for optical effects and also called the light vector.

4. TRANSVERSE NATURE OF ELECTROMAGNETIC WAVES

The electromagnetic waves are transverse in nature. In electromagnetic waves the electric and magnetic fields are mutually perpendiculr and also perpendicular to the directions of wave' propagation such that $\vec{E},\vec{B}$ and $\vec{K}$ form a right handed set ($\vec{K}$ is propagation vector along the direction of propagation.)

5. ELECTROMAGNETIC SPECTRUM

The electromagnetic waves have continuous wavelength starting from short gamma ray to long radiowaves. The orderly distribution of wavelength of em waves is called the electromagnetic spectrum. The complete spectrum is given in the following table.

S.No.	Name	Wavelength Range (m)	Frequency Range (Hz)
1	Gamma rays	$10^{-13} - 10^{-10}$	$3 \times 10^{21} - 3 \times 10^{18}$
2	X-rays	$10^{-10} - 10^{-8}$	$3 \times 10^{18} - 3 \times 10^{16}$
3	Ultraviolet rays	$10^{-8} - 4 \times 10^{-7}$	$3 \times 10^{16} - 7.5 \times 10^{14}$
4	Visible light	$4 \times 10^{-7} - 7.5 \times 10^{-7}$	$7.5 \times 10^{14} - 4 \times 10^{14}$
5	Infra red light	$7.5 \times 10^{-7} - 10^{-3}$	$4 \times 10^{14} - 3 \times 10^{11}$
6	Microwaves	$10^{-3} - 3 \times 10^{-2}$	$3 \times 10^{11} - 10^{10}$
7	Radio waves	$3 \times 10^{-2} - 10^{4}$	$10^{10} - 3 \times 10^{4}$

6. WAVELENGTH RANGE OF VISIBLE SPECTRUM

Visible light has a continuous wavelength starting from 400 nm to 750 nm ; fro convenience it is divided into 7 colours.

V	Violet	400 nm – 420 nm
I	Indigo	420 nm – 450 nm
B	Blue	450 nm – 500 nm
G	Green	500 nm – 570 nm
Y	Yellow	570 nm – 600 nm
O	Orange	600 nm – 650 nm
R	Red	650 nm – 750 nm

7. USES OF ELECTROMAGNETIC SPECTRUM

(i) γ - rays are highly penetrating, they can penetrate thick iron blocks. Due to high energy, they are used to produce nuclear reactions. Hard γ - rays are used in radiotherapy.

(ii) X-rays are used in medical diagnostics to detect fractures in bones, tuberculosis of lumgs, presence of stone in gallbladder and kidney. They are used in engineering to check flaws in bridges. In physics X-rays are used to study crystal structure.

(iii) Ultraviolet rays provide vitamin D. These are marmful for skin and eyes. They are used to sterilise drinkingwater and surgical istruments. They are used to detect invisible writing. forged documents, finger prints in farensic lab and to preserver food stuffs.

(iv) Infrared rays are used for long distance photography and for therapeutic purposes.

(v) Radiowaves are used for broadcasting programmes to distant places. According to frequency range, they are divided into following groups

(1) Medium frequency band or medium wave 0.3 to 3 MHz

(2) Short waves or short frequency band 3 MHz – 30 MHz

(3) Very high frequency (VHF) band 30 MHz to 300 MHz

(4) Ultahigh frequency (UHF) band 300 MHz to 3000 MHz

(5) Microwaves 3 GHz to 300 GHz

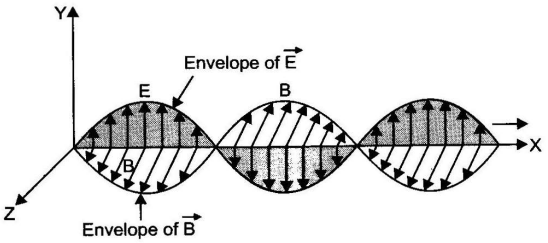
SOLVED PROBLEMS

1. ***What is meant by the transverse nature of electromagentic wave ? Draw a diagram showing the propagation of an electromagnetic wave along X-direction, indicating clearly the directions of oscillating electric and magnetic fields associated with it.***

Sol. Transverse Nature of Electromagnetic waves :

In an electromagnetic wave, the electric and magnetic rield vectors oscillate, perpendicular to the direction of propagation of wave. This is called transverse nature of electromagnetic wave.

In an electromagnetic wave, the three vectors $\vec{E},\vec{B}$ and $\vec{K}$ form a right handed system. According if a wave is propagating along X-axis, the electric field vector oscillates along Y-axis and magnetic field vector oscillates along Z-axis. Diagram is shown in fig.



2. ***Give two characteristics of electromagnetic waves. Write the expression for velocity of electromagnetic waves in terms of permittivity and permeability of the meidum.***

Sol. Characteristics of electromagnetic waves :

(i) Electromagnetic waves travel in free space with speed of light $c = 3 \times 10^8$ m/s.

(ii) Electromagnetic wave are transverse in nature.

Expression for velocity of em waves in vacuum, $c = \frac{1}{\sqrt{\mu_0 \varepsilon_0}}$

3. **Indentify the part of the electromagnetic spectrum which is :**

(i) suitable for radar systems used in aircraft navigation.

(ii) adjacent to low frequency end of the electromagnetic spectrum.

(iii) produced in nuclear reactions.

(iv) produced by bombarding a metal target by high speed electrons.

Sol. (i) Microwaves (ii) Readiowaves (iii) Gamma rays (iv) X-rays.

4. **Electromagnetic radioations with wavelength**

(i) λ_1 are used to kill germs in water purifiers.

(ii) λ_2 are used in TV communication system.

(iii) λ_3 play an important role in maintaining the earth's warmth.

Name the part of electromagnetic spectrum to which these radioations belong. Arrange these wavelength in decreasing order of their magnitude.

Sol. (i) λ_1 corresponds to ultraviolet spectrum.

(ii) λ_2 corresponds to radio waves

(iii) λ_3 corresponds to infrared order

$\lambda_2 > \lambda_3 > \lambda_1$.

5. ***Name the following constituent radiations of electromagnetic spectrum which***
(i) produce intense heating effect
(ii) is absorbed by ozone layer in the atmosphere
(iii) is used for studying crystal structure.
Write some more applications for each of these radiations.

Sol. (i) Infrared radioations produce intense heating effect.
One more Application : Infrared radiations are used for taking photographs during the conditions of fog and smoke etc.
(ii) Ultraviolet radiations are absorbed by the ozone layer in the atmosphere.
One more Application : Ultraviolet radiations are used to destroy becteria and for sterilizing surgical instruments.
(iii) X-rays are used to study crystal structure.
One more Application : X-rays are used to diagnose diseases and defects e.g., cract in bones, detection of tumous, stone in kidney and gall bladder etc.

6. ***Write the order of frequency range and one use of each of the followng electromagnetic radiations :***
(i) Microwaves
(ii) Ultraviolet rays
(iii) Gamma rays

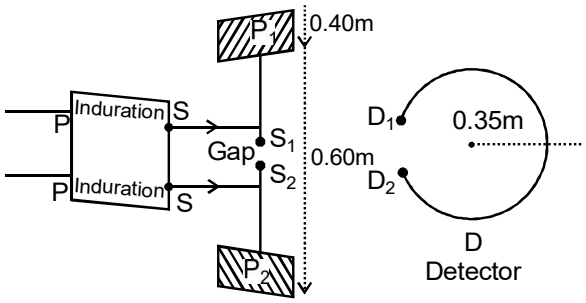
Sol. (i) Microwaves : Frequency range $\rightarrow 3 \times 10^{11}$ Hz – 1×10^{8} Hz. These are suitable for the rader systems, used in aircraft navigation.
(ii) Ultravilolet rays : Frequency range $\rightarrow 1 \times 10^{16}$ Hz – 8×10^{14} Hz. They are used to detect invisible writing, forged documents and finger prints.
(iii) Gamma rays : Frequency range $\rightarrow 5 \times 10^{20}$ Hz – 3×10^{19} Hz. Use $\rightarrow$ For the treatment of cancer cells.

7. ***Name the constituent radiation of electromagnetic spectrum which***
(a) is used in satellite communication.
(b) is used for studying crystal structure.
(c) is similar to the radiotions emitted during the decay of radioactive nuclei
(d) has its wavelength range between 390 nm and 700 nm
(e) is absorbed from sunlight by ozone layer.
(f) produces intense heating effect.

Sol. (a) Short radiowaves $\lambda < 10$ m or $v > 30$ MHz are used in satellite communication.
(b) X-rays are used for studying crystal structure.
(c) γ - radiation is similar to the radiation emitted during the decay of radioactive nuclei
(d) Visible radiation has a wavelength range of 390 nm – 700 nm.
(e) Ultraviolet light is absorbed from sunlight by ozone layer.
(f) Infrared radiation produces intense heating effect.

8. ***Draw the labelled diagram of Hertz's experimental set-up to produce electromagnetic waves. Explain the generation of electromangetic waves using this set-up.***

Sol. **Hertz's Experimental Arrangement :** It consists of two large metal spheres S_1 and S_2, which are attached to large metal plates P_1 and P_2. The spheres are connected to induction coil I. Induction coil provides high voltage across the gap.
A detector consisting of a single loop of wire connected to two spheres D_1 and D_2 is used to detect the electromanetic waves.



Generation of Electromangetic Waves : By interrupting current in induction coil, a high voltage is applied across the gap between S_1 and S_2. The high voltage so produced ionises the air across the jumping between the gap. The spark gap consists of electrons and ions produced due to ionisation of air. These charged particles oscillate back and forth which result in production of electromanetic waves is determined by the inductance and capacitance provided by plates. The frequency is given by wires that form the gap.

$$v = \frac{1}{2\pi\sqrt{LC}}$$

The circuit is equivalent to an L – nC circuit, where the coil provides the inductance and spherical electrodes provide the capacitance. As inductance L and capacitance C are very small, the frequency of oscillations $f = \frac{1}{2\pi\sqrt{LC}}$ is very high. Therefore, the circuit generates electromagnetic waves of very high frequency. The detector is placed in such a position that the magnetic field produced by the oscillating current is perpendicular to the plane of the detector coil. This oscillating magnetic across the gap. This clearly demonstrates the production of electromagnetic waves.

Hertz failed to detect the spark if the gap D_1, d_2 of detector coil was perpendicular to gap S_1 S_2. This By this experiment the electromagnetic waves of wavelength 5 m coul be produced.

9. Suppose that the electric field of an electromagnetic wave in vaccum is $\vec{E}$ = {(3.1 N/C cos (1.8 rad/m)y + (5.4 × 10⁶ rad/s) t } $\hat{i}$

(a) What is the direction of propagation ?

(b) What is the wavelength λ ?

(c) What is the frequency v ?

(d) What is the amplitude of the magnetic field part of the wave ?

(e) Write an expression for the magnetic field part of the wave.

Sol. (a) Wave is propagating along negative y-axis.

(b) Standard equation of wave is $\vec{E} = E_0 \cos(Ky + \omega t)\hat{i}$

Comparing the given equation with standard equation, we have

$$E_0 = 3.1 N/C, K = 1.8 rad/m, \omega = 5.4 \times 10^6 rad/s.$$

Propagation constant $K = \frac{2\pi}{\lambda}$ $\quad \therefore \quad \lambda = \frac{2\pi}{k} = \frac{2 \times 3.14}{1.8} m$ **= 3.49 m**

(c) We have $\omega = 5.4 \times 10^6$ rad/s

Frequency, $v = \frac{\omega}{2\pi} = \frac{5.4 \times 10^6}{2 \times 3.14} Hz = 8.6 \times 10^5$ Hz

(d) Amplitude of magnetic field, $B_0 = \frac{E_0}{c} = \frac{3.1}{3 \times 10^8} = 1.03 \times 10^{-8} T$

(e) The magnetic field is vibrating along Z-axis because $\vec{K}, \vec{E}, \vec{B}$ form a righd handed system

$\therefore$ Expression for magnetic field is

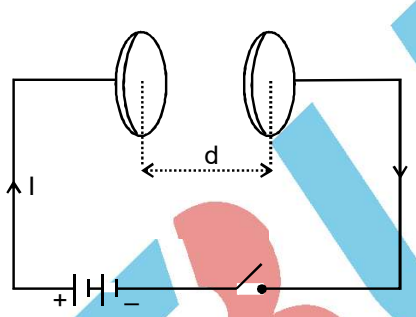
$$\vec{B} = B_0 \cos(Ky + \omega t)\hat{k} \quad = [1.03 \times 10^{-8}\ T \cos \{(1.8\ rad/m\}y + (5.4 \times 10^6\ rad/s)\ t]\ \hat{k}$$

10. Figure represents a capacitor made of two circular plates each of radius r = 12 cm and separatedby d = 5.0 mm. Thec apacitor is being charged by an external source. The charging current is constant I = 0.15 A.

(i) Calculate the rate of change of electric field between the plates.

(ii) Find the displacement current across the plates.

(iii) Is Kirchhoff's first rule valid at each plate of capacitor ? Explain.



Sol. (i) Let C be the capacitance of capacitor and q the instantaneous charge on plates, then

$$q = CV$$

$$\therefore \quad \frac{dq}{dt} = C\frac{dV}{dt}$$

If E isthe electric field between the plates, then V = Ed

$$\therefore \quad \frac{dq}{dt} = C\frac{d}{dt}(Ed)$$

i.e., $\quad I = C\,d\,\frac{dE}{dt}$

$$\therefore \quad \frac{dE}{dt} = \frac{1}{Cd} = \frac{1}{\frac{\varepsilon_0 A}{d}d} = \frac{1}{\varepsilon_0 A} = \frac{1}{\varepsilon_0 \pi r^2}$$

Here, I = 0.15 A, r = 12 cm = 12×10^{-2} m.

$\therefore$ Rate of change of electric field between the plates

$$\frac{dE}{dt} = \frac{0.15}{8.85\times10^{-12}\times3.14\times(12\times10^{-2})} = 3.14 \times 10^{11}\ Vm^{-1}\ s^{-1}$$

(ii) Displacement current $I_d = \varepsilon_0 A \frac{dE}{dt} = \varepsilon_0 A \frac{I}{\varepsilon_0 A} = I$ = conducting current = 0.15 A.

(iii) Yes, Kirchhoff's law holds at each plate of capacitor since displacement current is equal to conduction current.

EXERCISE - I UNSOLVED PROBLEMS

1. State four properties of electromagnetic waves.

2. Explain the terms (i) ground waves (ii) sky waves

3. Write Maxwell's equatins for electromagnetic waves.

4. How are electromagnetic waves produced ? Give the formula for frequency of waves produced.

5. What is height and role of ozone layer ?

6. Have you heard about the damage of ozone layer ? What factors do you think have caused this damag ?

7. In a plane electromagnetic wave, the electric field oscillates at a frequency of 2.0×10^{10} Hz. What is the wavelength of the wave ?

8. The electric field vector in an electromagnetic wave travelling in free space has amplitude 120 N/C. Determine electrosatic energy density and the amplitude of the magnetic field vector.

9. An electromagnetic wave of wavelength 1 mm is propagating along X-axis. The direction of magnetic field vector is along Z-axis. What is the frequency of wave ? What is the direction of prpagation of wave ?

10. Compare and contrast between x-rays and γ-rays ?

11. State complete electromagnetic spectrum. Give at least one use of each part.

12. What do you mean by ground waves and sky wave ? Why is the transmission of signals using ground wave restricted to frequencies less than about 1500 kHz ? Why cannot T.V. signals be broadcasted using sky waves ?

EXERCISE - II BOARD PROBLEMS

1. Name the electromagntic waves that have frequencies greater than those of ultraviolet light but less than those of gamma rays.

2. When can a charge acts a source of electromagnetic wave ? How are the directions of electric and magnetic field vectors, in an electromagnetic wave related to each other and to the direction of propagation of the wave ?
Which physical quantity, if any has the same value for wave belonging to the different parts of the electromagnetic spectrum ?

3. The oscillating electric field of an electromagnetic wave is given by

$$E_y = 30 \sin (2 \times 10^{11} t + 300 \pi x) \text{ Vm}^{-1}$$

(a) Obtain the value of wavelength of the electromangetic wave.
(b) Write down the epxression for oscillating electric field.

4. The oscillating magnetic field in a plane electromagnetic wave is given by

$$B_y = (8 \times 10^{-6}) \sin [2 \times 10^{11} t + 300 \pi x] \text{ T}$$

(i) Calculate the wavelength of the electromagnetic wave.
(ii) Write down the expression for the oscillations electric field.

5. Identify the part of the electromagnetic spectrum to whcih the following wavelengths belong

6. Name the electromagnetic readiations used for studying the crystal structure of solids.

7. To which regions of the electromagnetic spectrum, the following wavelengths belong ?
2,000 Å, 5,000 Å, 10,000 Å and 1.0 Å

8. It is necessary to use satellites for long distance TV transmission; why ?

9. Which constituent radiation of the electromagnetic spectrum is used
(i) in radar, (ii) to photograph internal parts of a human body, and
(iii) for taking photographs of the sky during light and foggy conditions ?
Give one reason for your answer in each case.

10. What is the ratio of speed of γ - rays and radiowaves in vacuum.?

11. Welders wear special goggles or face masks with glass windowns to protect their eyes from electromagnetic radiations. Name the radiations and write the range of their frequency.