# 8 Electromagnetic Waves

## Facts that Matter

- **Electromagnetic Waves**

Electromagnetic waves are self-sustaining oscillations of electric and magnetic fields in free space or vacuum. The electric and magnetic fields $E_x$ and $B_y$ are perpendicular to each other and to the direction of propagation. The $E_x$ and $B_y$ can be written

as $$E_x = E_0 \sin (kz - \omega t)$$

and $$B_y = B_0 \sin (kz - \omega t)$$

Here $K$ is related to the wavelength $k$ of the wave of the usual equation

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

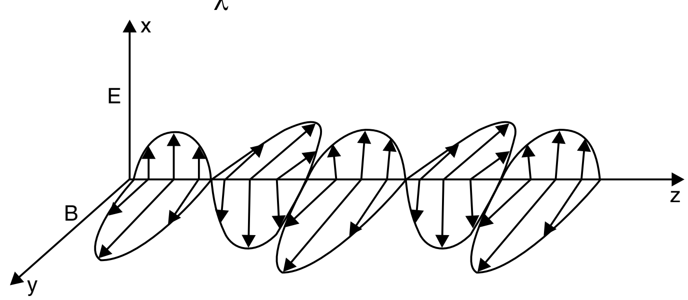


**Fig. 8.1**

- **Properties of Electromagnetic Waves**

(*i*) They have electric and magnetic field vibrations perpendicular to each other and perpendicular to the direction of propagation as shown in Fig. 8.1.
(*ii*) They do not require medium for their propagation.
(*iii*) They can ionise the gases.
(*iv*) They can penetrate the substances.
(*v*) They impart momentum and produce heat.
(*vi*) They can be polarised.
(*vii*) They interfere, diffract and scatter.
(*viii*) They can produce photoelectric effect.
(*ix*) They travel with the speed $3 \times 10^8$ m/s in free space or vacuum.
(*x*) They travel in straight line.
(*xi*) They do not deflect in electric or magnetic fields.

## • Spectrum of Electromagnetic Waves

The distribution of energy wavelength-wise is called spectrum. The spectrum of electromagnetic waves can be given wavelength-wise or frequency-wise as $\upsilon = \frac{c}{\lambda} = \frac{3 \times 10^8}{\lambda}$.

The spectrum of electromagnetic waves wavelength-wise is given in Fig. 8.2.

| $\gamma$-ray | $x$-ray | Ultraviolet wave | Visible VIBGYOR | Infrared | Micro wave | Radio TV |
|---|---|---|---|---|---|---|

← $10^{-10}$ m  $10^{-8}$ m  $4 \times 10^{-7}$ m  $7 \times 10^{-7}$ m  1 m  100 m →

**Fig. 8.2**

**Gama Rays (γ).** These are produced in nuclear reactions and also emitted by radioactive materials. They have very large range of wavelength $10^{-14}$ m to $10^{-10}$ m.

- They have high penetration power and small ionising power.
- They produce fluorensence in willemite like substances.
- They affect the photographic plate.
- These are used in medicine to destroy cancer cells.
- These are also used in nuclear research.

**X-Rays.** X-rays are produced by bombarding the heavy metal target by high energy electrons.

- X-rays are used.

(*i*) in detecting fractures, diseased organs, foreign matter like bullets, stones, glass, etc.

- Controlled X-ray is used to cure intractable skin diseases and malignani growths.
- for detecting pearls in oysters. For testing the uniformity of insulating materials and homogenity of timber.
- to examine defects in tyres, golf and tenis balls, cricket bat, etc.
- for detection of explosives, opium and banned foods and custom departments to detect gold, silver, etc.
- for investigating the structures of crystals, atomic and molecular alignments and properties in complex substances.

**Ultraviolet Rays.** These are produced by special lamps and very hot bodies. Ultraviolet rays have harmful effects on humans. Exposure to these radiations induces the production of more melanin, causing tanning of the skin.

- Ultraviolet radiations can be focussed into very narrow beams for high precision applications such as LASIK (Laser Assisted in Situ Keratomileusis) eye surgery.
- These are used to kill germs in water purifiers.
- They help in synthesizing vitamin D, when sunlight is exposed to skin.
- These are used for checking the mineral sample.
- These are used for the study of molecular structure.
- UV rays are used to kill bacteria and sterilize surgical instruments.

**Visible Light.** It is emitted or reflected from objects provides information about the world. Our eyes are sensitive for visible light. The light energy emitted by sun lies 50% in visible range.

**Infrared Radiations.** These are produced by hot bodies and molecules. These can be sensed by snakes. Infrared radiations sometimes referred to as heat waves. This is because water molecules present in most materials readily absorb infrared waves. Many other molecules like $CO_2$, $NH_3$ also absorb infrared radiations. After absorption, their thermal motion increases and get heated.

- Infrared lamps are used in physical therapy.
- These are used in earth's satellite, both for military purposes and other purposes also.
- Coal deposites are developed due I.R. heating.
- These radiations are used in solar water heaters and coolers.
- These are used for the study of molecules and purity of chemicals.
- These are used for producing dehydrated fruits.
- They play an important role in maintaining the earth's warmth or average temperature through the green house effect. In coming visible light (which passes relatively easily through the atmosphere) is absorbed by the earth's surface and reradiated as infrared radiations. These radiations are trapped by green house gases such as carbon dioxide, methane and water vapour.

**Micro Waves.** These are produced by special vacuum tubes such as klystrons, magnetrons.

- These are used in radar and aircraft navigation.
- These are used in microwaves ovens. In such ovens, the frequency of the microwaves is selected to match the resonant frequency of water molecules so that energy from the waves is transferred efficiently to the kinetic energy of the water molecules. This raises the temperature of any food containing water.

**Radio Waves.** These are produced by the accelerated motion of charges in conducting wires.

- These are used in radio and TV communication systems.
- These are used in cellular phones to transmit voice communication in the range of ultra high frequency band.
- These are used for amplitude modulation and frequency modulation.

## • Displacement Current

Let there be a capacitor in a circuit carrying current $I$ for its charging. If there is point $P$ near to the plates of the circuit as shown in Fig. 8.3. Applying Ampere's circuital law for surface $S_1$,

$$\oint_{S_1} B\ dl = \mu_o I \qquad ...(i)$$

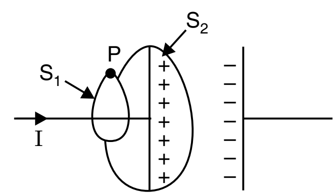


Fig. 8.3

Also for surface $S_2$,

$$\oint_{S_2} B\ dl = \mu_0 (0) = 0 \qquad ...(ii)$$

(since there is no current in the capacitor)

The loop $S_1$ and $S_2$ are infinitely closed, therefore, the magnetic field due to these two loops at point $P$ must be zero. But

$$\oint_{S_1} B\ dl \neq \oint_{S_2} B\ dl$$

Thus, Ampere's circuital law appears to be inconsistant.

- To remove this inconsistency Maxwell used the concept of displacement current. According to Maxwell *the current produced due change in electric field is called displacement current.*
- The displacement current is given by

$$I_D = \varepsilon_0 \frac{\partial Q}{\partial t}$$

where $\partial Q$ is the change in magnetic flux in time $\partial t$.

- σ displacement current

$$I_D = \varepsilon_0 \frac{\partial Q}{\partial t}$$

Applying Gauss's law $Q = \frac{1}{\varepsilon_0}(q)$

$$I_D = \varepsilon_0 \frac{\partial}{\partial t}\left[\frac{1}{\varepsilon_0}(q)\right]$$

$$= \frac{\partial q}{\partial t}$$

$$= I_C \qquad \text{(conduction current)}$$

- Displacement current = conduction current.
- For second loop $S_2$ in Fig. 8.3, current inside the capacitor due to variation of electric field called displacement current.

Therefore, $\oint_{S_2} B\, dl = \mu_0 (I_D)$

∵ $I_D = I_C = I$

⇒ $\oint_{S_2 B} dl = \mu_o (I)$

Thus in Fig. 8.3 $\oint_{S_1 B} dl = \oint_{S_2 B} dl$

- Maxwell used four equations to explain the behaviour of electromagnetic waves. These equations are called Maxwell's equations. Following are the Maxwell's equations.

 (*i*) $\oint_B dl = \mu_o \left[\varepsilon_0 \frac{\partial Q}{\partial t} + I_c\right]$ This modified Ampere's circuital law

 (*ii*) $\oint_E dl = -\frac{\partial Q}{\partial t}$ (Faraday's law)

 (*iii*) $\oint_E ds = \frac{1}{\varepsilon_0}(q)$ (Gauss theorem)

 (*iv*) $\oint_B .ds = 0$ (Gauss theorem)

- **Hertz's Experiment.** Hertz demonstrated that Maxwell's predictions were true by installing a spark gap (two conductors separated by short gap as shown in Fig. 8.4) at the centre of a parabolic metallic mirror.

 A wire ring connected to another spark gap was placed about 1.5 m away at the focus of another parabolic collector in line with the first. A spark jumping across the first gap caused a smaller spark to jump across the gap in the ring 1.5 m away. Hertz showed that the waves travelled in straight lines and that could be reflected by metal sheet just as light waves are reflected by mirror.

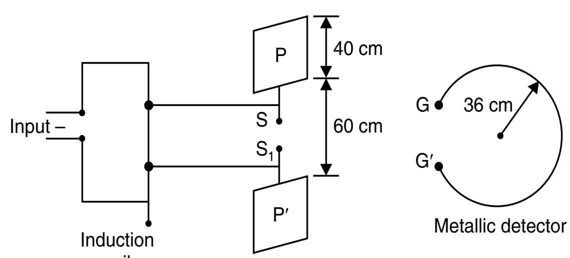

Fig. 8.4

## • Propagation of Electromagnetic Waves

During the propagation of electromagnetic waves electric and magnetic field oscillate perpendicular to each other in same phase both perpendicular to the direction of propagation. The varying electric field produces varying magnetic field and vice-versa.

If $\frac{\partial E_x}{\partial Z}$ be the variation of electric field per unit distance, then the electric field at the point $A$ and $B$ can be given as $E_x$ and $\left(E_x + \frac{\partial E_x}{\partial z} dz\right)$ respectively [Fig. 8.5]

$\therefore$ closed loop $ABCD$, applying the Faraday's law

$$\oint_{ABCDE} dl = E_x\ d + \frac{\partial E_x}{\partial z} dz.dx - E_x\ dX$$

or
$$\frac{\partial Q_B}{\partial t} = \frac{\partial E_x}{\partial z}.dz.dx$$

or
$$\frac{\partial}{\partial t}.B_y A = \frac{\partial E_x}{\partial z}.A$$

or
$$\frac{\partial B_y}{\partial t} = \frac{\partial E_x}{\partial z}$$

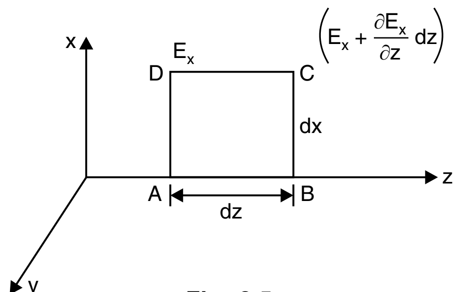


Fig. 8.5

Thus, change in electric field is the source of change in magnetic field.

If $\frac{\partial B_y}{\partial z}$ be the variation of magnetic field per unit distance then the magnetic field at point $A$ and $B$ can be given as $B_y$ and $B_y + \frac{\partial B_y}{\partial z}.dz$ respectively [Fig. 8.6]

Applying Maxwell's law for loop $ABCD$.

$$\oint_{ABCD} B\ dl = \left(B_y + \frac{\partial B_y}{\partial z} dz\right) d_y - B_y\ dy$$

or
$$\mu_0\ \varepsilon_0 \frac{\partial Q_E}{\partial t} = \frac{\partial B_y}{\partial z}.\ dz\ dy$$

or
$$\mu_0\ \varepsilon_0 \frac{\partial E_x\ A}{\partial t} = \frac{\partial B_y}{\partial z}.\ A$$

or
$$\frac{\partial E_x}{\partial t} = \frac{1}{\mu_0 \varepsilon_0}.\frac{\partial B_y}{\partial z}$$

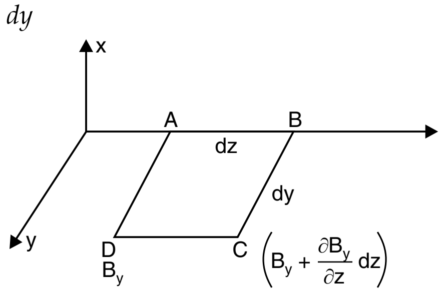


Fig. 8.6

thus, changing magnetic field is the source of changing electric field.

## • Velocity of Electromagnetic Waves

Since changing electric field is the source of changing magnetic field and vice-versa.

$$\frac{\partial B}{\partial t} = \frac{\partial E}{\partial x} \quad ...(i)\ (x \text{ is the direction propagation})$$

and $$\frac{\partial E}{\partial t} = \frac{1}{\mu_0 \varepsilon_0}\frac{\partial B}{\partial x} \quad \text{...(ii)}$$

Putting the value of $\partial B$ from Eq. (*i*) in Eq. (*ii*)

$$\frac{\partial E}{\partial t} = \frac{1}{\mu_0 \varepsilon_0}\frac{\partial E}{\partial x}\cdot\frac{\partial t}{\partial x}$$

or $$\left(\frac{\partial x}{\partial t}\right)^2 = \frac{1}{\mu_0 \varepsilon_0}$$

or $$C^2 = \frac{1}{\mu_0 \varepsilon_0} \qquad \left(\because \frac{\partial x}{\partial t} = C \text{ the velocity of wave}\right)$$

or $$C = \frac{1}{\sqrt{\mu_0 \varepsilon_0}}$$

This is the expression for the velocity of electromagnetic wave in free space.

- The velocity of electromagnetic wave in medium having relative permeability $\mu_r$ and relative permittivity $\varepsilon_r$.

  The Velocity of electromagnetic wave in medium

  or $$C_m = \frac{1}{\sqrt{\mu_0 \mu_r \,.\, \varepsilon_0 \varepsilon_r}}$$

- The refractive index of the medium,

  or $$n = \frac{C}{C_m}\ \frac{1/\sqrt{\mu_0 \varepsilon_0}}{1/\sqrt{\mu_0 \mu_r\, \varepsilon_0 \varepsilon_r}}$$

  or $$n = \sqrt{\mu_r\, \varepsilon_r}$$

- In a region of free space with electric field $E_0$, there is an energy density $\left(\frac{1}{2}\varepsilon_0 E_0^2\right)$. Energy density associated with a magnetic field $B_0$ is $\left(\frac{1}{2}\frac{{B_0}^2}{\mu_0}\right)$. As electromagnetic waves contains both electric and magnetic fields, there is a non-zero energy density associated with it.
- An electromagnetic wave carries energy and momentum. Thus, it exerts pressure, called *radiation pressure.* If the total energy transferred to a surface in time $t$ is $U$, the magnitude of the total momentum delivered to this surface,

  $$P = \frac{U}{C} \text{ (for complete absorption)}$$

- In electromagnetic waves energy densities of electric field and magnetic field are equal

  *i.e.,* $$\frac{1}{2}\varepsilon_0 {E_0}^2 = \frac{1}{2}\frac{{B_0}^2}{\mu_0}$$

  $\Rightarrow$ $$\frac{{E_0}^2}{{B_0}^2} = \frac{1}{\mu_0 \varepsilon_0}$$

or $$\frac{E_0}{B_0} = \frac{1}{\sqrt{\mu_0 \varepsilon_0}}$$

or $$\frac{E_0}{B_0} = C$$

It is the velocity of electromagnetic wave or light in free space.

For any other medium.

$$\frac{E}{B} = v$$

## QUESTIONS FROM TEXTBOOK

**8.1.** *Figure shows a capacitor made of two circular plates each of radius 12 cm, and separated by 5.0 cm. The capacitor is being charged by an external source (not shown in the figure). The charging current is constant and equal to 0.15A.*

*(a) Calculate the capacitance and the rate of charge of potential difference between the plates.*

*(b) Obtain the displacement current across the plates.*

*(c) Is Kirchhoff's first rule (junction rule) valid at each plate of the capacitor? Explain.*

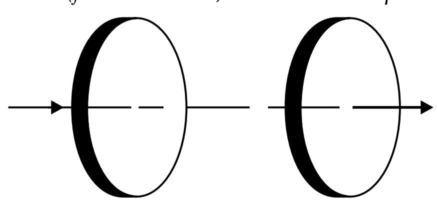

**Fig. 8.7**

**Sol.** (*a*) Given, $R = 12 \text{ cm} = 0.12 \text{ m}$

$d = 5.0 \text{ mm} = 5 \times 10^{-3}$

$I = 0.15 \text{ A}$

$\varepsilon_0 = 8.85 \times 10^{-12} \text{ C}^2 \text{ N}^{-1} \text{ m}^{-2}$

∴ Area, $A = \pi R^2 = 3.14 \times (0.12)^2 \text{ m}^2$

Capacitance of parallel plate capacitor is given by

$$\boxed{C = \frac{\varepsilon_0 A}{d}}$$

$$= \frac{8.85 \times 10^{-12} \times (3.14) \times (0.12)^2}{5 \times 10^{-3}}$$

$$= 80.1 \times 10^{-12} = 80.1 \text{ pF}$$

Now, $$\boxed{q = CV}$$

or, $$\frac{dq}{dt} = C \times \frac{dV}{dt}$$

or, $$I = C \times \frac{dV}{dt} \qquad \left[\because I = \frac{dq}{dt}\right]$$

or, $$\frac{dV}{dt} = \frac{I}{C} = \frac{0.15}{80.1 \times 10^{-12}}$$

$$= 1.87 \times 10^9 \text{ Vs}^{-1}$$

(*b*) Displacement current is equal to the conduction current *i.e.,* 0.15 A.

(*c*) Yes, Kirchhoff's first rule is valid at each plate of the capacitor provided. We take the current to be the sum of the conduction and displacement currents.

**8.2.** *A parallel plate capacitor (Fig.) made of circular plates each of radius R = 6.0 cm has a capacitance C = 100 pF. The capacitor is connected to a 230 V ac supply with a (angular) frequency of 300 rad* $s^{-1}$.

*(a) What is the rms value of the conduction current?*

*(b) Is the conduction current equal to the displacement current?*

*(c) Determine the amplitude of* ***B*** *at a point 3.0 cm from the axis between the plates.*

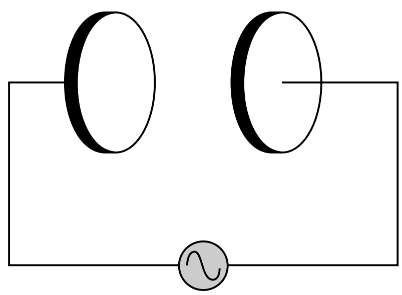

**Fig. 8.8**

**Sol.** (*a*) Here,

$$R = 6.0 \text{ cm}$$

$$C = 100 \text{ pF} = 100 \times 10^{-12} \text{ F}$$

$$\omega = 300 \text{ rad s}^{-1}$$

$$E_{rms} = 230 \text{ V}$$

$$\boxed{I_{rms} = \frac{E_{rms}}{X_C}} = \frac{E_{rms}}{\frac{1}{\omega C}} = E_{rms} \times \omega C$$

$\therefore$ $$I_{rms} = 230 \times 300 \times 100 \times 10^{-12}$$

$$= 6.9 \times 10^{-6} \text{ A} = 6.9 \ \mu\text{A}$$

(*b*) Yes, $I = I_D$, whether $I$ is steady *d.c.* or *a.c.* This is shown below:

$$\boxed{I_D = \varepsilon_0 \frac{d(\phi_E)}{dt}} = \varepsilon_0 \frac{d}{dt}(EA) \qquad (\because \phi_E = EA)$$

or, $$I_D = \varepsilon_0 A \frac{dE}{dt}$$

$$= \varepsilon_0 A \frac{d}{dt}\left(\frac{Q}{\varepsilon_0 A}\right) \qquad \left(\because E = \frac{\sigma}{\varepsilon_0} = \frac{Q}{\varepsilon_0 A}\right)$$

or, $$I_D = \varepsilon_0 A \times \frac{1}{\varepsilon_0 A} \frac{dQ}{dt} = \frac{dQ}{dt} = I$$

(*c*) We know that

$$B = \frac{\mu_0}{2\pi}\frac{r}{R^2} I_D$$

This formula goes through even if $I_D$ (and therefore $B$) oscillates in time. The formula shows that they oscillate in phase. Since $I_D = I$, we have

$$B = \frac{\mu_0 rI}{2\pi R^2}$$

If $I = I_0$, the maximum value of current, then amplitude of $B$ = maximum value of $B$

$$= \frac{\mu_0 rI_0}{2\pi R^2} = \frac{\mu_0 r\sqrt{2} I_{rms}}{2\pi R^2} \qquad \left(\because I_0 = \sqrt{2} I_{rms}\right)$$

$$= \frac{4\pi \times 10^{-7} \times 0.03 \times \sqrt{2} \times 6.9 \times 10^{-6}}{2 \times 3.14 \times (0.06)^2} \text{ T}$$

$$= 1.63 \times 10^{-11} \text{ T.}$$

**8.3.** *What physical quantity is the same for X-rays of wavelength $10^{-10}$ m, red light of wavelength 6800 Å and radio waves of wavelength 500 m?*

**Sol.** The speed for X-ray, red light and radio waves in vacuum is the same and is $C = 3 \times 10^8$ ms$^{-1}$.

**8.4.** *A plane electromagnetic wave travels in vacuum along z-direction. What can you say about the directions of its electric and magnetic field vectors? If the frequency of the wave is 30 MHz, what is its wavelength?*

**Sol.** $\vec{E}$ and $\vec{B}$ lie in $x$-$y$ plane and are mutually perpendicular,

since $C = \nu\lambda$

Thus $\lambda = \frac{c}{\nu} = \frac{3 \times 10^8}{30 \times 10^6} = 10$ m.

**8.5.** *A radio can tune in to any station in the 7.5 MHz to 12 MHz band. What is the corresponding wavelength band?*

**Sol.**

$$\lambda_1 = \frac{c}{\nu_1} = \frac{3 \times 10^8}{7.5 \times 10^6} = 40 \text{ m}$$

$$\lambda_2 = \frac{c}{\nu_2} = \frac{3 \times 10^8}{12 \times 10^6} = 25 \text{ m}$$

Hence, wavelength band is 40 m – 25 m.

**8.6.** *A charged particle oscillates about its mean equilibrium position with a frequency of $10^9$ Hz. What is the frequency of the electromagnetic waves produced by the oscillator?*

**Sol.** The frequency of electromagnetic wave is the same as that of oscillating charged particle about its equilibrium position; which is $10^9$ Hz.

**8.7.** *The amplitude of the magnetic field part of a harmonic electromagnetic wave in vacuum is $B_0$ = 510 nT. What is the amplitude of the electric field part of the wave?*

**Sol.** Given $B_0 = 510 \text{ nT} = 510 \times 10^{-9}$ T

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

For electromagnetic waves,

$$\boxed{C = \frac{E_0}{B_0}}$$

or, $$E_0 = C\,B_0$$
$$= 3 \times 10^8 \times 510 \times 10^{-9}$$
$$= 153\ \text{NC}^{-1}$$

**8.8.** *Suppose that the electric field amplitude of an electromagnetic wave is $E_0$ = 120 N/C and that its frequency is $\nu$ = 50.0 MHz.*

*(a) Determine, $B_0$, $\omega$, k, and $\lambda$.* *(b) Find expressions for **E** and **B**.*

**Sol.** (*a*) (*i*)

$$\boxed{\frac{E_0}{B_0} = C}$$

or $$B_0 = \frac{E_0}{C} = \frac{120}{3 \times 10^8}\ \text{T}$$
$$= 40 \times 10^{-8}\ \text{T} = 400 \times 10^{-9}\ \text{T} = 400\ \text{nT}$$

(*ii*) $$\boxed{\omega = 2\pi\,\nu} = 2\pi \times 50 \times 10^6 = 3.14 \times 10^8\ \text{rad s}^{-1}$$

(*iii*) $$\boxed{k = \frac{2\pi}{\lambda}} = \frac{2\pi\,\nu}{\nu\lambda} = \frac{2\pi\,\nu}{C} = \frac{\omega}{C} = \frac{\pi \times 10^8}{3 \times 10^8}\ \text{rad m}^{-1}$$
$$= \frac{\pi}{3}\ \text{rad m}^{-1} = 1.05\ \text{rad m}^{-1}$$

(*iv*) $$\boxed{C = \nu\lambda;}\ \lambda = \frac{C}{\nu} = \frac{3 \times 10^8}{50 \times 10^6}\ \text{m} = \frac{300}{50} = \mathbf{6\ m}.$$

(*b*) Let the electromagnetic wave travel along +*x*-axis, and $\vec{E}$ and $\vec{B}$ are along *y*-axis and *z*-axis respectively. Then,

$$\boxed{\vec{E}_y = E_0 \sin(kx - \omega t)\,\hat{j}}$$
$$= 120 \sin(1.05x - 3.14 \times 10^8\ t)\,\hat{j}\ \ \text{NC}^{-1}$$
$$\vec{B}_z = B_0 \sin(kx - \omega t)\,\hat{k}$$
$$= 400 \sin(1.05x - 3.14 \times 10^8\ t)\,\hat{k}\ \ \text{nT}$$

**8.9.** *The terminology of different parts of the electromagnetic spectrum is given in the text. Use the formula E = h$\nu$ (for energy of a quantum of radiation: photon) and obtain the photon energy in units of eV for different parts of the electromagnetic spectrum. In what way are the different scales of photon energies that you obtain related to the sources of electromagnetic radiation.*

**Sol.** Energy of photon

$$E = h\nu$$

or $$E = h\frac{C}{\lambda}$$
$$h = 6.62 \times 10^{-34}\ \text{js}, \quad C = 3 \times 10^8\ \text{m s}^{-1}$$

If $\lambda$ is in metre, $E$ in $J$, then we divide by $1.6 \times 10^{-19}$ to convert $E$ into eV.

$\therefore$ $$E = \frac{hc}{\lambda \times 1.6 \times 10^{-19}}\ \text{eV}$$

(1) **γ-rays.** 1 ranges from $10^{-10}$ m to less that $10^{-14}$ m

$$\therefore \qquad \text{Energy} = \frac{6.62 \times 10^{-34} \times 3 \times 10^{8}}{10^{-10} \times 1.6 \times 10^{-19}} \text{ eV}$$

$$= 12.4 \times 10^{3}\ eV \approx 10^{4} \text{ eV}$$

Thus for $\lambda = 10^{-10}$ m, energy = $10^4$ eV.

For $\lambda = 10^{-14}$ m, energy = $10^8$ eV.

Energy of γ-rays between $10^4$ to $10^8$ eV.

(2) ***X*-rays.** 1 ranges from $10^{-8}$ m to $10^{-13}$ m.

For $\lambda = 10^{-8}$

$$\therefore \qquad \text{Energy} = \frac{6.62 \times 10^{-34} \times 3 \times 10^{8}}{10^{-8} \times 1.6 \times 10^{-19}} \text{ eV}$$

$$= 124 \approx 10^{2} \text{ eV}$$

For $\lambda = 10^{-13}$ m, energy = $10^7$ eV.

(3) **Ultraviolet radiations.** λ ranges from $4 \times 10^{-7}$ m to $6 \times 10^{-10}$ m.

For $\lambda = 4 \times 10^{-7}$

$$\therefore \qquad \text{Energy} = \frac{6.62 \times 10^{-34} \times 3 \times 10^{8}}{4 \times 10^{-7} \times 1.6 \times 10^{-19}} \text{ eV}$$

$$= 3.1 \text{ eV} \approx 10^{0} \text{ eV}$$

Energy of ultraviolet radiations vary between $10^0$ to $10^3$ eV.

(4) **Visible radiations.** λ ranges from $4 \times 10^{-7}$ m to $7 \times 10^{-7}$ m.

For $\lambda = 4 \times 10^{-7}$, energy = $10^0$ eV (as proved above)

For $\lambda = 7 \times 10^{-7}$

$$\therefore \qquad \text{Energy} = \frac{6.62 \times 10^{-34} \times 3 \times 10^{8}}{7 \times 10^{-7} \times 1.6 \times 10^{-19}} \text{ eV}$$

$$= 1.77 \text{ eV} \approx 10^{0} \text{ eV}$$

(5) **Infrared radiations.** λ ranges from $7 \times 10^{-7}$ m to $7 \times 10^{-4}$ m.

For $\lambda = 7 \times 10^{-7}$, energy = $10^0$ eV (as proved above)

For $\lambda = 7 \times 10^{-4}$,

the energy is $\frac{1}{1000}$ times, *i.e.*, of the order of $10^{-3}$ eV.

(6) **Micro waves.** λ ranges from 1 mm to 0.3 m.

For $\lambda$ = 1 mm or $10^{-3}$,

$$\text{Energy is equal to} \qquad E = \frac{6.62 \times 10^{-34} \times 3 \times 10^{8}}{10^{-3} \times 1.6 \times 10^{-19}} \text{ eV}$$

$$= 1.24 \times 10^{-3} \text{ eV} \approx 10^{-3} \text{ eV.}$$

For $\lambda$ = 0.3 m, energy = $4.1 \times 10^{-6}$ eV ≈ $10^{-6}$ eV.

(7) **Radio waves.** λ ranges from 1 m to few km.

For $\lambda$ = 1 m

Energy is equal to $E = \dfrac{6.62 \times 10^{-34} \times 3 \times 10^{8}}{10^{0} \times 1.6 \times 10^{-19}}$ eV

$= 1.24 \times 10^{-6}$ eV $\approx 10^{-6}$ eV.

Energy for $\lambda$ of the order of few km $\approx 10^{-6}$ ev.

Energy of a photon that a source produces indicates the spacing of relevant energy levels of the source.

**8.10.** *In a plane electromagnetic wave, the electric field oscillates sinusoidally at a frequency of $2.0 \times 10^{10}$ Hz and amplitude 48 V $m^{-1}$.*

*(a) What is the wavelength of the wave?*

*(b) What is the amplitude of the oscillating magnetic field?*

*(c) Show that the average energy density of the **E** field equals the average energy density of the **B** field. [$c = 3 \times 10^8$ m $s^{-1}$.]*

**Sol.** Here, $\nu = 2 \times 10^{10}$ Hz, $E_0 = 48$ $Vm^{-1}$.

(*a*) $$\lambda = \frac{c}{\nu} = \frac{3 \times 10^8}{2 \times 10^{10}} \text{ m} = 1.5 \times 10^{-2} \text{ m}$$

(*b*) $$B_0 = \frac{E_0}{c} = \frac{48}{3 \times 10^8} \text{ T} = 1.6 \times 10^{-7} \text{ T}$$

(*c*) Energy density in electric field,

$$u_E = \frac{1}{2} \varepsilon_0 E^2$$

Energy density in magnetic field,

$$u_B = \frac{1}{2\mu_0} B^2$$

Using $E = cB$, $$u_E = \frac{1}{2} \varepsilon_0 (cB)^2 = c^2\left(\frac{1}{2} \varepsilon_0 B^2\right)$$

But $$c = \frac{1}{\sqrt{\mu_0 \varepsilon_0}}$$

$\therefore$ $$u_E = \frac{1}{\mu_0 \varepsilon_0}\left(\frac{1}{2} \varepsilon_0 B^2\right) = \frac{1}{2\mu_0} B^2 = u_B$$

**8.11.** *Suppose that the electric field part of an electromagnetic wave in vacuum is **E** = {(3.1 N/C) cos [(1.8 rad/m) y + (5.4 × $10^6$ rad/s)t]}$\hat{\boldsymbol{i}}$.*

*(a) What is the direction of propagation?*

*(b) What is the wavelength $\lambda$?*

*(c) What is the frequency $\nu$?*

*(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*) The wave is propagating along negative $y$ direction *i.e.,* along $-\hat{j}$.

(*b*) Comparing the given equation with the equation

$$E = E_0 \cos(ky + \omega t)\,\hat{i}$$

$$E_0 = 3.1 \text{ NC}^{-1}, \quad k = 1.8 \text{ rad m}^{-1}$$
$$\omega = 5.4 \times 10^6 \text{ rad s}^{-1}$$

we know that

$$\omega = 2\pi \nu$$

or, $$5.4 \times 10^6 = 2\pi \nu = 2\pi \times \frac{c}{\lambda}$$

or, $$\lambda = \frac{2\pi c}{5.4 \times 10^8} = \frac{2\pi \times 3 \times 10^8}{5.4 \times 10^8}$$
$$= 3.5 \text{ m}$$

(*c*) Again $$\nu = \frac{c}{\lambda} = \frac{3 \times 10^8}{3.5} = 0.86 \times 10^8 \text{ Hz}$$
$$= 86 \times 10^6 \text{ Hz} = 86 \text{ MHz}$$

(*d*) We know that

$$\boxed{c = \frac{E_0}{B_0}}$$

$$\therefore \quad B_0 = \frac{E_0}{c} = \frac{3.1}{3 \times 10^8} = 1.03 \times 10^{-8} \text{ T}$$
$$= 0.0103 \times 10^{-6} \text{ T} = 0.0103 \ \mu\text{T}$$

(*e*) Expression of magnetic field part of the wave

$$B = B_0 \cos (ky + \omega t)$$
$$= 1.03 \times 10^{-8} \cos \{(1.8 \text{ rad/m})\, y + (5.4 \times 10^6 \text{ rad/s})\, t\}$$

$E$ is along $\hat{i}$ and $c$ is along $-\hat{j}$, $c$ is the direction of $\vec{E} \times \vec{B}$

$$-\hat{j} = \hat{i} \times ?$$

Clearly? is in the direction of $\hat{k}\left(\hat{k} \times \hat{i} = \hat{j}\right)$ and $\left(\hat{i} \times \hat{k} = -\hat{j}\right)$

Thus $\vec{B}$ is completely represented as

$$\vec{B} = 1.03 \times 10^{-8} \cos \{(1.8 \text{ rad/m})\, y + (5.4 \times 10^6 \text{ rad/s})\, t\}\, \hat{k}.$$

**8.12.** *About 5% of the power of a 100 W light bulb is converted to visible radiation. What is the average intensity of visible radiation*

*(a) at a distance of 1m from the bulb?* *(b) at a distance of 10 m?*

*Assume that the radiation is emitted isotropically and neglect reflection.*

**Sol.** Power converted into visible radiation,

$$P = \frac{5}{100} \times 100 \text{ W} = 5 \text{ W}$$

$$\boxed{\text{Intensity} = \frac{\text{Energy}}{\text{Area} \times \text{Time}} = \frac{\text{Power}}{\text{Area}} = \frac{P}{4\pi r^2}}$$

(*a*) $$\text{Intensity}, I = \frac{5}{4 \times 3.14 \times 1 \times 1} = 0.4 \text{ Wm}^{-2}$$

(b) $$I = \frac{5}{4 \times 3.14 \times 10 \times 10} \text{ Wm}^{-2}$$
$$= 0.004 \text{ Wm}^{-2}$$

**8.13.** *Use the formula $\lambda_m T = 0.29$ cm K to obtain the characteristic temperature ranges for different parts of the electromagnetic spectrum. What do the numbers that you obtain tell you?*

**Sol.** We know, every body at a given temperature *T*, emits radiations of all wavelengths in certain range. For a black body, the wavelength corresponding to maximum intensity of radiation at a given temperature *T* is given, according to Wein's law, by the radiation

$$\boxed{\lambda_m T = 0.29 \text{ cmK}} \quad \text{or} \quad T = \frac{0.29}{\lambda_m}$$

For $$\lambda_m = 10^{-6} \text{ m} = 10^{-4} \text{ cm}, \quad T = \frac{0.29}{10^{-4}} = 2900 \text{ K}.$$

Temperature for other wavelengths can be similarly found. These numbers tell us the temperature ranges required for obtaining radiations in different parts of the electromagnetic spectrum. Thus to obtain visible radiation, say, $\lambda_m = 5 \times 10^{-5}$ cm, the source should have a temperature $T = \dfrac{0.29}{5 \times 10^{-5}} \simeq 6000$ K

It is to be noted that, a body at lower temperature will also produce this wavelength but not with maximum intensity.

**8.14.** *Given below are some famous numbers associated with electromagnetic radiations in different contexts in physics. State the part of the electromagnetic spectrum to which each belongs.*

*(a) 21 cm (wavelength emitted by atomic hydrogen in interstellar space).*

*(b) 1057 MHz (frequency of radiation arising from two close energy levels in hydrogen; known as Lamb shift).*

*(c) 2.7 K [temperature associated with the isotropic radiation filling all space-thought to be a relic of the 'big-bang' origin of the universe].*

*(d) 5890 Å – 5896 Å [double lines of sodium].*

*(e) 14.4 keV [energy of a particular transition in $^{57}Fe$ nucleus associated with a famous high resolution spectroscopic method (Mössbauer spectroscopy)].*

**Sol.** (*a*) Radio waves (short wavelength end)

(*b*) Radio waves (short wavelength end)

(*c*) Microwaves

(*d*) Visible region (yellow)

(*e*) *X*-rays (or soft $\gamma$-rays) region.

**8.15.** *Answer the following questions:*

*(a) Long distance radio broadcasts use short-wave bands. Why?*

*(b) It is necessary to use satellites for long distance TV transmission. Why?*

*(c) Optical and radiotelescopes are built on the ground but X-ray astronomy is possible only from satellites orbiting the earth. Why?*

*(d) The small ozone layer on top of the stratosphere is crucial for human survival. Why?*

*(e) If the earth did not have an atmosphere, would its average surface temperature be higher or lower than what it is now?*

*(f) Some scientists have predicted that a global nuclear war on the earth would be followed by a severe 'nuclear winter' with a devastating effect on life on earth. What might be the basis of this prediction?*

**Sol.** (*a*) This is because ionosphere reflects waves in these bands.

(*b*) It is so because television signals are not properly reflected by the ionosphere. Therefore, for reflection of signals, satellites are needed.

(*c*) Atmosphere absorbs *X*-rays, while visible and radiowaves can penetrate it. That is why optical and radio telescopes can work on earth's surface but *X*-ray astronomical telescopes must be used on satellites orbiting the earth.

(*d*) The small ozone layer on the top of the stratosphere absorbs ultraviolet radiations, γ-rays etc., from the sun. It also absorbs cosmic radiations. So, these radiations, which can cause genetic damage to the living cells, are prevented from reaching the earth. Thus, the small ozone layer on top of the stratosphere is crucial for human survival.

(*e*) The temperature of the earth would be lower because the green house effect of the atmosphere would be absent.

(*f*) The clouds produced by a global nuclear war would perhaps cover substantial parts of the sky preventing solar light from reaching many parts of the globe. This would cause a 'winter'.

# MORE QUESTIONS SOLVED

## I. VERY SHORT ANSWER TYPE QUESTIONS

**Q. 1.** *Name the EM waves used for studying crystal structure of solids. What is its frequency range?*

**Ans.** *X*-rays are used for studying crystals structure of solids. Their frequency range is $10^{16}$ Hz to $3 \times 10^{21}$ Hz.

**Q. 2.** *Name the part of electromagnetic spectrum which is suitable for*

*(i) radar systems used in aircraft navigation.*

*(ii) treatment of cancer tumours.*

**Ans.** (*i*) Microwave

(*ii*) Gamma rays

**Q. 3.** *Special devices like the klystron value or the magnetron valve, are used for production of electromagnetic waves. Name these waves and also write one of their applications.*

**Ans.** Klystron valve or magnetron valve are used for production of Microwave.

Microwaves are used in Microwave Ovens.

**Q. 4.** *Name the electromagnetic radiation to which the following wavelengths belong:*

*(a)* $10^{-2}$ *m*

*(b) 1 Å*

**Ans.** (*a*) Microwaves [Range: 0.3 to $10^{-3}$ m]

(*b*) *X*-rays [Range: $3 \times 10^{-8}$ to $1 \times 10^{-13}$ m]

**Q. 5.** *What is the name given to that part of electromagnetic spectrum which is used for taking photographs of earth under foggy conditions from the great height?*

**Ans.** Infrared rays.

**Q. 6.** *Write the expression for speed of electromagnetic waves in free space.*

**Ans.** The speed of electromagnetic waves in free space,

$$v = \frac{1}{\sqrt{\mu_0 \varepsilon_0}}$$

where, $\mu_0$ = absolute permeability and $\varepsilon_0$ is the absolute permeability of the free space.

**Q. 7.** *What is the cause of conduction current?*

**Ans.** The cause of conduction current is the flow of electrons in the conductor under the effect of potential difference applied.

**Q. 8.** *Rewrite the following in the descending order of wavelength:*
*Infrared rays, radio waves, γ-rays, microwaves.*

**Ans.** Radio waves, microwaves, infrared rays and γ-rays.

**Q. 9.** *The charging current for a capacitor is 0.25 A. What is the displacement current across its plates?*

**Ans.** Displacement current is 0.25 A. Since displacement current is equal to conduction current.

**Q. 10.** *'Microwaves are used in Radar'. Why?*

**Ans.** Due to their smaller wavelength, microwaves can be transmitted as beam signals in a particular direction, much better than radio waves because microwaves do not bend around the corners of any obstacle coming in their path.

**Q. 11.** *What is the effect of electromagnetic waves on charged particles?*

**Ans.** These can accelerate charges and produce oscillating currents.

**Q. 12.** *The electric vector of a plane EM wave oscillates sinusoidally at a frequency of $4 \times 10^{14}$ Hz. What is the wavelength of the wave?*

**Ans.** $7.5 \times 10^{-7}$ m. $\lambda = \frac{C}{v} = \frac{3 \times 10^8}{4 \times 10^{14}} = 0.75 \times 10^{-6} = 0.75 \times 10^{-7}$ m .

**Q. 13.** *What is the approximate wavelength range for visible part of electromagnetic spectrum ?*

**Ans.** 390 nm to 770 nm.

**Q. 14.** *Identify the part of the electromagnetic spectrum to which the following wavelengths belong.*
*(i) 1 mm (ii) $10^{-11}$ m.*

**Ans.** (*i*) Microwave
(*ii*) Gamma rays

**Q. 15.** *State the applications of Ultraviolet radiations.*

**Ans.** Ultraviolet radiations are used (*i*) to preserve the food stuff, (*ii*) to sterilizing the surgical instruments.

**Q. 16.** *State two applications of Infrared radiations.*

**Ans.** Infrared radiations are used (*i*) to treat muscular strain, (*ii*) for taking photographs during the conditions of fog, smoke etc.

**Q. 17.** *For which frequency of light, the eye is most sensitive?*

**Ans.** The eye is most sensitive to the light of wavelength

$\lambda = 5600 \times 10^{-10}$ m. Therefore, its frequency

$$\nu = \frac{c}{\lambda} = \frac{3 \times 10^8}{5600 \times 10^{-10}} = 5.36 \times 10^{14} \text{ Hz.}$$

## II. SHORT ANSWER TYPE QUESTIONS

**Q. 1.** *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 radiations emitted during decay of radioactive nuclei.*
*(d) has its wavelength range between 390 nm and 770 nm.*
*(e) is absorbed from sunlight by ozone layer.*
*(f) produces intense heating effect.*

**Ans.** (*a*) 30 MHz to 3 GHz (It can be transmitted either through satellites or direct line of sight using tall towers)

(*b*) *X*-ray

(*c*) γ-ray

(*d*) Visible rays

(*e*) UV rays

(*f*) Infrared rays

**Q. 2.** *The oscillating electric field of an electromagnetic wave is given by:*

$$E_y = 30 \sin [2 \times 1011\ t + 300\ \pi x]\ Vm^{-1}$$

*(a) Obtain the value of the wavelength of the electromagnetic wave.*

*(b) Write down the expression for the oscillating magnetic field.*

**Ans.**

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

(*a*) $$K = 300\ \pi = \frac{2\pi}{\lambda} \Rightarrow \lambda = \frac{1}{150} = 6.7 \times 10^{-3}\ \text{m}$$

(*b*) $$B_z = (10^{-7}) \sin [2 \times 10^{11}\ t + 300\ \pi x]\ \text{T}$$

**Q. 3.** *Explain the following terms:*

*(i) Ground waves* *(ii) Space waves* *(iii) Sky waves.*

**Ans.** (*i*) *Ground waves.* A radio wave that travels directly from one point to another following the surface of the earth is called ground wave or surface wave.

(*ii*) *Space waves.* A radio wave that travels directly from a high transmitting antenna to the receiving station is called space wave.

(*iii*) *Sky waves.* A radio wave transmitted towards the sky and reflected by the ionosphere towards the desired location of the earth is called a sky wave.

**Q. 4.** *A plane electromagnetic wave travels, in vacuum, along the y-direction. Write the (i) ratio of the magnitudes and (ii) the direction of its electric and magnetic field vectors.*

**Ans.** (*i*) $\frac{E}{B} = c$ = speed of light

(*ii*) For an electromagnetic wave travelling along *y*-direction its electric and magnetic field vectors are along *x*-axis and *z*-axis respectively.

**Q. 5.** *Why sky wave propagation of electromagnetic waves cannot be used for TV transmission? Suggest two methods by which range of TV transmission can be increased.*

**Ans.** *TV* signals have frequencies of 100–200 MHz, which penetrate ionosphere (frequencies > 30 MHz cannot be used), hence cannot be used for *TV* transmission. Two methods by which range of *TV* transmission can be increased:

(*a*) use of tall antenna

(*b*) use of repeaters between transmitters and receivers (line-of-sight transmission).

**Q. 6.** *What is the wavelength of a photon whose energy is 1 eV? In which part of the electromagnetic spectrum is it?*

**Ans.** $$\text{Energy} = (h\nu) = \frac{hc}{\lambda}$$

$$\therefore \quad \lambda = \frac{hc}{\text{energy}} = \frac{6.625 \times 10^{-34} \times 3 \times 10^{8}}{1.6 \times 10^{-19}}$$

or, $$\lambda = 1.24 \times 10^{-5}\ \text{m}$$

Infrared rays.

**Q. 7.** *Write any two applications of X-rays.*

**Ans.** *X*-rays are used

(*i*) for the detection of explosives, opium and gold in the body of the smugglers.

(*ii*) in detecting fractures, diseased organs in human body.

**Q. 8.** *The following table gives the wavelength range of some constituents of this electromagnetic spectrum:*

| *S. No.* | *Wavelength range* |
|---|---|
| *1* | *1 mm to 700 nm* |
| *2* | *400 nm to 1 nm* |
| *3* | *1 nm to $10^{-3}$ nm* |
| *4* | *< $10^{-3}$ nm* |

*Select the wavelength range and name the electromagnetic waves that are:*

*(i) widely used in the remote switches of household electronic devices.*

*(ii) produced in nuclear reactions.*

**Ans.** (*i*) Infrared waves (wavelength range: 1 mm to 700 nm)

(*ii*) Gamma rays (wavelength range: $10^{-3}$ nm).

**Q. 9.** *Which of the following, if any, can act as a source of electromagnetic waves?*

*1. A charge moving with a constant velocity.*

*2. A charge moving in a circular orbit.*

*3. A charge at rest.*

*Give reason.*

*Identify the part of the electromagnetic spectrum, to which waves of frequency (i) $10^{20}$ Hz, (ii) $10^9$ Hz belong. Find the ratio of their velocities in glass (n = 1.5).*

**Ans.** None of the three act as a source of electromagnetic waves.

An oscillating electric dipole radiates electromagnetic waves.

(*i*) γ-rays

(*ii*) Radio waves

The ratio of their velocities in glass will be the same and is given by,

$$v = \frac{c}{n} = \frac{3 \times 10^8}{1.5} = 2 \times 10^8.$$

**Q. 10.** *The magnetic field of an electromagnetic wave oscillates parallel to a y-axis and is given by $B_y = B_0 y \sin (kz - \omega t)$. (a) In what direction does the wave travel and (b) parallel to which axis does the associated electric field oscillate?*

**Ans.** (*a*) The phase is changing with $z$ and $t$. So, the wave is travelling along $z$-direction.

(*b*) Since $\vec{E}, \vec{B}$ and the direction of propagation are mutually perpendicular therefore $\vec{E}$ should be along the $x$-axis.

**Q. 11.** *A variable frequency AC source is connected to a capacitor. Will the displacement current increase or decrease with increase in frequency?*

**Ans.** Increase in frequency causes decrease in impedance of the capacitor and consequent in the current which equals displacement current between the plates.

## III. LONG ANSWER TYPE QUESTIONS

**Q. 1.** *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 oscillating electric field.*

**Ans.** Given equation is

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

Comparing the given equation with the equation of magnetic field varying sinusoidally with $x$ and $t$

$$B_y = B_0 \sin \left(\frac{2\pi x}{\lambda} + \frac{2\pi t}{T}\right)$$

we get $\quad \dfrac{2\pi}{\lambda} = 300\,\pi$

$\therefore \quad \lambda = \dfrac{2}{300} = 0.0067 \text{ m}$

and $\quad B_0 = 8 \times 10^{-6}$ T

(*i*) Wavelength of the electromagnetic wave

$$\lambda = 0.0067 \text{ m}$$

(*ii*) $\quad \boxed{E_0 = CB_0} = 3 \times 10^8 \times 8 \times 10^{-6}$

$$= 24 \times 10^2 = 2400 \text{ Vm}^{-1}$$

$\therefore$ The required expression for the oscillating electric field is

$$E_z = E_0 \sin \left(\frac{2\pi x}{\lambda} + \frac{2\pi t}{T}\right)$$

$$= 2400 \sin (300\pi\, x + 2 \times 10^{11} \text{ t}) \text{ V/m.}$$

**Q. 2.** *Write any four characteristics of electromagnetic waves. Give two uses of (i) radio-waves (ii) Microwaves.*

**Ans.** Characteristics of electromagnetic waves:

(*i*) Electromagnetic waves are produced by accelerating or oscillating charge.

(*ii*) E.M. waves do not require any material medium for their propagation.

(*iii*) E.M. waves travel in free space with a velocity $C = \dfrac{1}{\sqrt{\mu_0 \varepsilon_0}}$ which is equal to the velocity of light ($c = 3 \times 10^8$ m/s).

(*iv*) E.M. waves are transverse in nature.

*Uses of Radio waves:*

(*i*) They are used in radio and *TV* communication systems.

(*ii*) Cellular phones use radio waves to transmit voice communication in the ultrahigh frequency (UHF) band.

*Uses of Microwaves:*

(*i*) Microwaves are used in Radar systems for aircraft navigation.

(*ii*) Microwave ovens are used for cooking purposes.

**Q. 3.** *Distinguish between sky wave and space wave propagation. Give a brief description with the help of suitable diagrams indicating how these waves are propagated.*

**Ans.** Sky wave and space wave propagation. See Q. 3 in short answer type section.
*Diagram.* Various propagation modes of electromagnetic waves (EMW) is shown below.

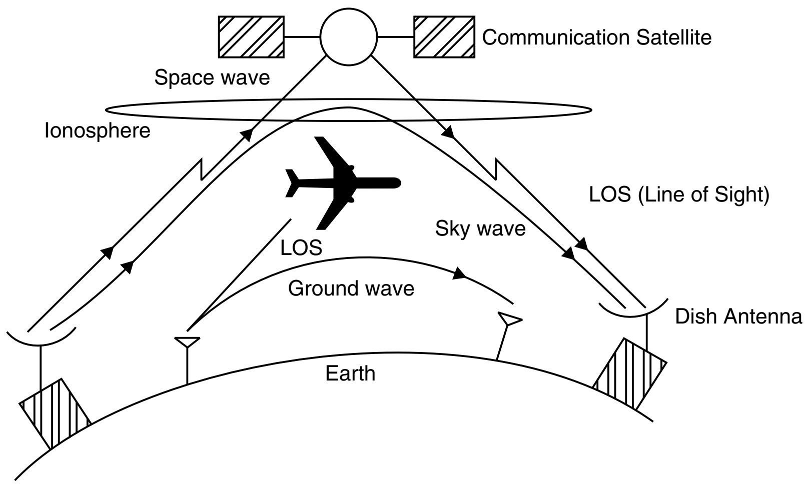


**Fig. 8.9**

**Q. 4.** *Draw a labelled diagram of Hertz's experimental set-up to produce electromagnetic waves. Explain the generation of electromagnetic waves using this set-up.*

**Ans.** *Hertz's Experiment.* Figure shows Hertz's experimental set-up used for producing electromagnetic waves.

Two large metal plates $P$ and $P'$ are connected to metal sphere $S$ and $S'$. The spheres are connected to an induction coil. By interrupting current in the coils, a sudden high voltage is set-up across the gap. This voltage ionises the air in the gap which produces oscillating current in the gap $SS'$. This process results in the production of electromagnetic waves. These waves are detected by detector which consists of a single loop of wire connected to spheres $G$ and $G'$.

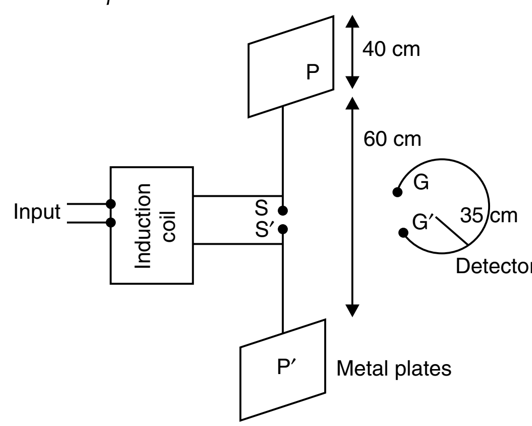


**Fig. 8.10**

**Q. 5.** *What is intensity of electromagnetic wave? Give its relation in terms of electric field E and magnetic field B.*

**Ans.** Intensity of electromagnetic wave is defined as the energy crossing per second per unit area perpendicular to the direction of propagation of electromagnetic waves. The intensity of electromagnetic wave at a point is

$$\boxed{I = U_{av}\, c}$$

where $$U_{av} = \frac{1}{2}\varepsilon_0 E_0^2 = \frac{1}{2}\frac{B_0^2}{\mu_0}$$

and $c$ is the velocity of electromagnetic wave.

$$\therefore \quad I = \frac{1}{2}\varepsilon_0 E_0^2\, c = \frac{1}{2}\frac{B_0^2}{\mu_0}\, c$$

Here $E_0$ and $B_0$ are maximum values of electric field and magnetic field respectively.

# QUESTIONS ON HIGH ORDER THINKING SKILLS (HOTS)

**Q. 1.** *Green light of mercury has a wavelength 5.5 × $10^{-5}$ cm.*

*(a) What is the frequency in MHz and period in micro second?*

*(b) What is the wavelength in glass, if the refractive index of glass is 1.5? Given, velocity of light is 3 × $10^8$ $ms^{-1}$.*

**Ans.** (*a*)
$$\nu = \frac{c}{\lambda} = \frac{3\times10^8 \text{ m/s}}{5.5\times10^{-7} \text{ m}}$$

or,
$$\nu = \frac{3\times10^8}{5.5\times10^{-7}\times10^6}\text{ MHz} = 5.45 \times 10^8 \text{ MHz.}$$

$$T = \frac{1}{\nu} = \frac{5.5\times10^{-7}\text{ m}}{3\times10^8 \text{ m/s}} = \frac{5.5\times10^{-7}}{3\times10^8}\times10^6\,\mu\text{s}$$

$$= 1.83 \times 10^{-9}\ \mu\text{s}$$

(*b*)
$$\mu = \frac{c}{v} \quad \text{or} \quad v = \frac{c}{\mu} = \frac{3\times10^8}{1.5} = 2 \times 10^8 \text{ m/s.}$$

$$\lambda = \frac{C_g}{\nu_g}$$

$$\lambda = \frac{2\times10^8}{5.45\times10^8}$$

$$\lambda = \frac{200}{545}$$

$$x = 0.36 \text{ m} = 36 \text{ cm.}$$

**Q. 2.** *What is meant by the transverse nature of electromagnetic waves? Draw a diagram showing the propagation of an electromagnetic wave along the x-direction, indicating clearly the directions of the oscillating electric and magnetic fields associated with it.*

**Ans.** Transverse nature of electromagnetic waves means the electric and magnetic fields in an electromagnetic wave are perpendicular to each other and to the direction of propagation.

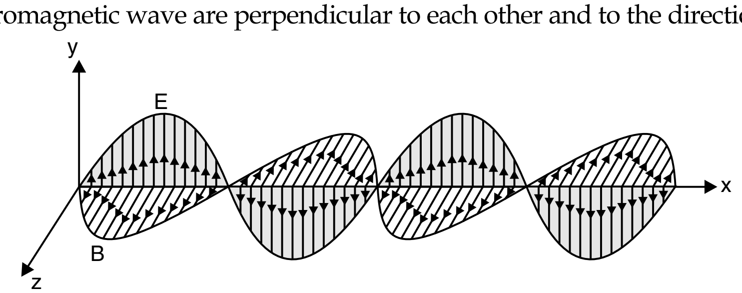


**Fig. 8.11**

**Q. 3.** *A radio transmitter operates at a frequency of 880 kHz, and a power of 10 kW. Find the number of photons per second emitted.*

**Ans.** Number of photons

$$\boxed{n = \frac{P}{h\nu}} = \frac{10\times10^3}{6.6\times10^{-34}\times880\times10^3}$$

$$= 1.171 \times 10^{31}$$

**Q. 4.** *Electromagnetic waves travel in a medium at a speed of $2 \times 10^8$ $ms^{-1}$. The relative permeability of the medium is 1.0. Calculate the relative permittivity.*

**Ans.** Given,

$$v = 2 \times 10^8 \text{ ms}^{-1}, \quad \mu_r = 1$$
$$C = 3 \times 10^8 \text{ m/s}$$

Using the formula,

$$v = \frac{1}{\sqrt{\mu\varepsilon}} \qquad \text{(speed of electromagnetic wave in a medium)}$$

or,
$$v = \frac{1}{\sqrt{\mu_0 \, \mu_r \, (\varepsilon_0 \, \varepsilon_r)}}$$

or,
$$v = \frac{1}{\sqrt{\mu_0 \, \varepsilon_0}} \times \frac{1}{\sqrt{\mu_r \, \varepsilon_r}}$$

or,
$$\varepsilon_r = \frac{c^2}{\nu^2 \, \mu_r} = \frac{(3 \times 10^8)^2}{(2 \times 10^8)^2 \times 1} = 2.25$$

**Q. 5.** *A parallel-plate capacitor with rectangular plates is being discharged. Consider a rectangular loop centred on the plates and between them. The loop measures by 2a, the plate measures 2a by 4a. What fraction of the displacement current is encircled by the loop?*

**Ans.** Displacement current,

$$I_d = \varepsilon_0 \frac{d\phi_E}{dt} = \varepsilon_0 \, A \frac{dE}{dt}$$
$$= \varepsilon_0 \, A \frac{d}{dt}\left(\frac{q}{\varepsilon_0 \, A'}\right)$$

where $A'$ is the area of each plate of the capacitor

∴
$$I_d = \frac{A}{A'} \frac{dq}{dt} = \frac{(a)(2a)}{(2a)(4a)} \frac{dq}{dt}$$
$$= \frac{1}{4} I.$$

**Q. 6.** *A plane electromagnetic wave propagating in the x-direction has a wavelength of 10.0 mm. The electric field is in the y-direction and its maximum magnitude is 60 V $m^{-1}$. Write suitable equations for the electric and magnetic fields as a function of x and t.*

**Ans.**

$$E_y = E_{0y} \sin\left[\frac{2\pi}{\lambda}(ct - x)\right]$$
$$B_z = B_{0z} \sin\left[\frac{2\pi}{\lambda}(ct - x)\right]$$
$$B_{0z} = \frac{E_{0y}}{c}$$

Putting value,

$$B_{0z} = \frac{60 \text{ v/m}}{3 \times 10^8 \text{ m/s}}$$
$$= 2 \times 10^{-7} \text{ T.}$$

**Q. 7.** *Find the amplitude of the electric field in a parallel beam of light of intensity 8.0 W/m².*

**Ans.** The intensity of plane electromagnetic wave is given by

$$I = U_{av}c = \frac{1}{2}\varepsilon_0 E_0^2 c$$

or, $$E_0 = \left(\frac{2I}{\varepsilon_0 c}\right)^{1/2}$$

or, $$E_0 = \left[\frac{2 \times 8.0}{(8.85 \times 10^{-12}) \times (3 \times 10^8)}\right]^{1/2}$$

$$= 77.6 \text{ NC}^{-1}$$

**Q. 8.** *The intensity of the sunlight reaching the earth is 1380 Wm$^{-2}$. Calculate the amplitudes of electric and magnetic field in the light wave. Assume the light to be a plane monochromatic wave.*

**Ans.** Intensity of plane monochromatic wave,

$$\boxed{I = \frac{1}{2}\varepsilon_0 E_0^2 c}$$

or, $$E_0 = \sqrt{\frac{2I}{\varepsilon_0 c}}$$

or, $$E_0 = \sqrt{\frac{2 \times 1380}{8.85 \times 10^{-12} \times 3 \times 10^8}} \text{ NC}^{-1}$$

$$= 1.02 \times 10^3 \text{ NC}^{-1}.$$

Amplitude of magnetic field,

$$B_0 = \frac{E_0}{c}$$

$$= \frac{1.02 \times 10^3}{3 \times 10^8} T = 3.4 \times 10^{-6} \text{ T}$$

$$= 3.4\ \mu\text{T}.$$

**9.** *Two students A and B prepare the following Table about the electromagnetic waves. Rewrite the table in its corrected form.*

| | *Direction of* | | | *Peak Value of* | |
|---|---|---|---|---|---|
| *Student* | *Electric field* | *Magnetic field* | *Propagation* | *Electric field* | *Magnetic field* |
| *A* | Along *X*-axis | Along *Y*-axis | Along *Y*-axis | *E* | *B* = *CE* |
| *B* | Along *Y*-axis | Along *Z*-axis | Along *X*-axis | *E* = *CB* | *B* |

**Ans.**

| | *Direction of* | | | *Peak value of* | |
|---|---|---|---|---|---|
| *Student* | *Electric field* | *Magnetic field* | *Propagation* | *Electric field* | *Magnetic field* |
| *A* | Along *X*-axis | Along *Y*-axis | Along *Z*-axis | *E* | $B = \frac{E}{C}$ |
| *B* | Along *Y*-axis | Along *X*-axis | Along *Z*-axis | *E* = *CB* | *B* |

**10.** *The velocity of propagation (in vacuum) and the frequency of (i) X-rays and (ii) radio waves are denoted by $(v_1, n_1)$ and $(v_2, n_2)$ respectively. How do the value of (a) $v_1$ and $v_2$ (b) $n_1$ and $n_2$ compare with each other?*

**Ans.** (*a*) $\frac{v_1}{v_1} > 1$ or $v_1 = v_1$ (*b*) $\frac{n_1}{n_2} > 1$ or $n_1 > n_2$.

**11.** *Name the electromagnetic waves used for the following and arrange them in increasing order of their penetrating power.*

(*a*) *Water purification* (*b*) *Rewrite sensing* (*c*) *Treatment of cancer.*

**Ans.** (*a*) Ultra violet waves (*b*) Micro waves (*c*) Gama rays

In increasing order of penetration powers of given waves can be written as, (*b*) remote sensing < (*a*) water purification < (*c*) treatment of cancer.

**12.** *Let the wavelengths of electromagnetic waves used quite often for*

(*i*) *killing germs in household water purifier*

(*ii*) *remote sensing (iii) be labelled as $\lambda_1$, $\lambda_2$ and $\lambda_3$, arrange $\lambda_1$, $\lambda_2$ and $\lambda_3$ in increasing order.*

**Ans.** $\lambda_3 < \lambda_1 < \lambda_2$.

**13.** *A plane electromagnetic wave of angular frequency ω is propagating with velocity C along the Z-axis. Write to vector equations of oscillating electric and magnetic fields and show those fields diagrametically.*

**Ans.** $E_x = E_0 \sin (kz - \omega t)$

and $B_y = E_0 \sin (kz - \omega t)$

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

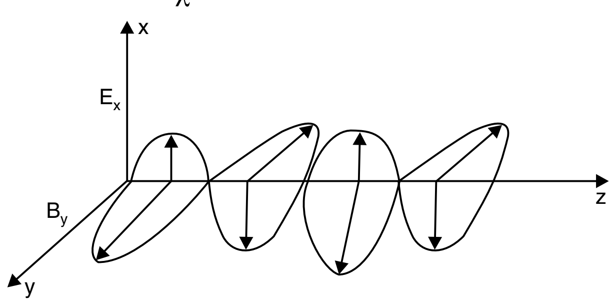


**Fig. 8.12**

# MULTIPLE CHOICE QUESTIONS

**1.** The frequencies of *X*-rays, *Y*-rays and ultra violet rays are respectively *a*, *b* and *c*. Then

(*a*) $a < b, b > c$ (*b*) $a > b, b > c$ (*c*) $a > b, b < c$ (*d*) $a < b, b < c$

**2.** The velocity of light in vacuum can be changed by changing

(*a*) frequency (*b*) amplitude (*c*) wavelength (*d*) None of these

**3.** These are 3 wavelengths $10^7$ m, $10^{-10}$ m, $10^{-7}$ m. Find their respective names

(*a*) Radiowaves, X-Rays, visible rays (*b*) X-Rays, Visible rays, Radiowaves

(*c*) X-Rays, *Y*-Rays, Visible rays (*d*) Visible rays, *Y*-rays, X-rays

**4.** The velocity of electromagnetic wave is parallel to

(*a*) $\vec{B} \times \vec{E}$ (*b*) $\vec{E} \times \vec{B}$ (*c*) $\vec{E}$ (*d*) $\vec{B}$

5. Which of the following statement is true?
   (*a*) Velocity of light is constant in all media
   (*b*) Velocity of light in vacuum is maximum.
   (*c*) Velocity of light is same in all reference frames.
   (*d*) Locus of nature have identical form in all reference frames.
6. Which of the following is a natural resource of gamma rays?
   (*a*) Radio-cobalt (*b*) Radio-phosphorus (*c*) Radiogas (*d*) Radio-carbon
   (*e*) Radio-iodine
7. The velocity of light is maximum in
   (*a*) diamond (*b*) water (*c*) vacuum (*d*) glass
8. The mean electric energy density between the plates of charged capacitor is (Here $q$ = charge on the capacitor and $A$ = area of the capacitor plate)
   (*a*) $\frac{q^2}{2E_0A^2}$ (*b*) $\frac{q}{2E_0A^2}$ (*c*) $\frac{q^2}{2E_0A}$ (*d*) none of these.
9. If the wavelength of light 4000 Å then the number of waves in 1 mm length will be
   (*a*) 25 (*b*) 0.25 (*c*) $0.25 \times 10^4$ (*d*) $2.5 \times 10^4$
10. Sodium lamps are used in foggy conditions because
    (*a*) yellow light is scattered less by the fog particles
    (*b*) yellow light is scattered more by the fog particles
    (*c*) yellow light is unaffected during its passage through the fog
    (*d*) wavelength of yellow light is the mean of the visible part of the spectrum.
11. If $\lambda_v$, $\lambda_x$ and $\lambda_m$ represent the wavelengths of visible light, *x*-rays and microwaves respectively, then
    (*a*) $l_m > l_x > l_v$ (*b*) $l_v > l_m > l_x$ (*c*) $l_v > l_x > l_m$ (*d*) $l_m > l_v > l_x$
12. The r.m.s. value of the electric field of the light coming from the sun is 720 $NC^{-1}$. The average total energy density of the electromagnetic wave is
    (*a*) $3.3 \times 10^{-3}$ $Jm^{-3}$ (*b*) $4.58 \times 10^{-6}$ $Jm^{-3}$ (*c*) $6.37 \times 10^{-9}$ $Jm^{-3}$ (*d*) $81.35 \times 10^{-12}$ $Jm^{-3}$
13. The speed of electromagnetic waves in a medium of dielectric constant 2.25 and relative permeability 4 is
    (*a*) $1.10^8$ m/s (*b*) $25 \times 10^8$ m/s (*c*) $2 \times 10^8$ m/s (*d*) $3 \times 10^8$ m/s
14. The amplitude of the sinusoidally oscillating electric field of the plane wave is 60 V/m. Then the amplitude of the magnetic field is
    (*a*) $2 \times 10^7$ T (*b*) $6 \times 10^7$ T (*c*) $6 \times 10^{-7}$ T (*d*) $2 \times 10^{-7}$ T
15. The correct arrangement of colours in the descending order of their wavelength is
    (*a*) yellow, violet, green, orange (*b*) orange, yellow, green, violet
    (*c*) violet, green, yellow, orange (*d*) yellow, green, orange, violet

## Answers

| | | | | |
|---|---|---|---|---|
| **1.** (*a*) | **2.** (*d*) | **3.** (*a*) | **4.** (*b*) | **5.** (*b*) |
| **6.** (*c*) | **7.** (*c*) | **8.** (*a*) | **9.** (*c*) | **10.** (*a*) |
| **11.** (*d*) | **12.** (*b*) | **13.** (*a*) | **14.** (*d*) | **15.** (*b*). |

# TEST YOUR SKILLS

**1.** For electromagnetic waves, write the relationship between amplitudes of electric and magnetic field.

**2.** Name the scientist, who first developed and operated the first transmitter and receiver of electromagnetic waves.

**3.** The ozone layer in the atmosphere is crucial for human survival. Why?

**4.** Why do long distance radio broadcasts used shortwave bands?

**5.** What is the ratio of speed of infrared rays and ultraviolet rays in vacuum?

**6.** Arrange the given electromagnetic radiations in the descending order of their frequencies : Infra-red, *X*-rays, Ultra-violet and Gamma rays.

**7.** Why is the transmission of signals using ground waves restricted to frequencies up to 1500 kHz?

**8.** Give a reason to show that microwaves are better signals for long transmission than radiowaves.

**9.** In a plane electromagnetic wave, the electric field oscillates sinusoidally at a frequency of $2 \times 10^{10}$ Hz and amplitude 48 $Vm^{-1}$. (*a*) What is the wavelength of the wave? (*b*) What is the amplitude of the oscillating magnetic field ? (*c*) Find the total average density of the electromagnetic field of the wave.

**10.** Suppose that the electric field part of an electromagnetic wave in vacuum is

$E = \{(3.1\ N/C) \cos [(1.8\ rad/m\ \lambda + (5.4 \times 10^6\ rad/s)t]\}\ i$

(*a*) What is the direction of propagation?

(*b*) What is the frequency λ?

(*c*) What is the frequency?

(*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.

**11.** A 100 watts incandescent lamp radiates all its energy in sinusoidal electromagnetic wave and that energy is emitted uniformly in all directions. Calculate maximum electric and magnetic field intensities at a distance of 2 m from the lamp.

**12.** Name the part of the electromagnetic spectrum of wavelength $10^{-2}$ m and mention its one application.

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

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

(*i*) Calculate the wavelength of the electromagnetic wave.

(*ii*) Write down the expression for the oscillating electric field.

**14.** The oscillating electric field of an electromagnetic wave is given by :

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

(*a*) Obtain the value of the wavelength of the electromagnetic wave.

(*b*) Write down the expression for the oscillating electric field.

**15.** The bombardment of a metal target, by high energy electrons, can result in the production of electromagnetic waves. Name these waves.

**16.** Identify the following electromagnetic radiations as per the wavelengths given below. Write the application of each.

(*a*) $10^{-3}$ nm (*b*) $10^{-3}$ m (*c*) 1 nm

**17.** Identify the following electromagnetic radiations as per the frequencies given below. Write one applications of each.

(*a*) $10^{20}$ Hz (*b*) $10^9$ Hz (*c*) $10^{11}$ Hz

❑❑❑