CHAPTER 8

ELECTROMAGNETIC WAVES

8.1 INTRODUCTION

A brief survey of the electromagnetic waves. We have learnt that an electric current produces a magnetic field. Also a magnetic field changing with time produces an electric field. Can an electric field changing with time produce a magnetic field ? *James Clerk Maxwell* (1831-1879), argued that this was indeed the case—an electric field changing with time produces a magnetic field. Maxwell noticed that Ampere's circuital law is inconsistent namely, makes non-unique predictions for the magnetic field in situations where electric current changes with time. He showed that consistency requires an additional source of magnetic field, this is called *displacement current*. This made the laws of electricity and magnetism symmetrical.

Maxwell formulated a set of four equations, called *Maxwell's equations*. With the help of these equations, he predicted that electric and magnetic fields dependent on time and space propagate as transverse waves, called *electromagnetic waves*. His discovery that electromagnetic waves travel with the speed of light led him to a remarkable conclusion that light is an electromagnetic wave. *Heinrich Hert*, in 1865, successfully demonstrated the existence of electromagnetic waves. A few years later, *Guglielmo Marconi* of Italy succeeded in transmitting electromagnetic waves over distances of several kilometres. His experiments brought a revolution in communication which we are witnessing even today.

8.2 MAXWELL'S DISPLACEMENT CURRENT

1. *Discuss the inconsistency in Ampere's circuital law. What modification was made by Maxwell in this law ? What is displacement current ? Conduction and displacement currents are individually discontinuous, but their sum is continuous. Comment.*

Inconsistency of Ampere's circuital law. According to Ampere's circuital law, the line integral of the magnetic field $\vec{B}$ *along any closed loop C is proportional to the current I passing through the closed loop, i.e.,*

$$\oint_C \vec{B} \cdot \vec{dl} = \mu_0 I \qquad ...(1)$$

In 1864, Maxwell showed that the equation (1) is logically inconsistent. To prove this inconsistency, we consider a parallel plate capacitor being charged by a battery as shown in Fig. 8.1(*a*). As the charging

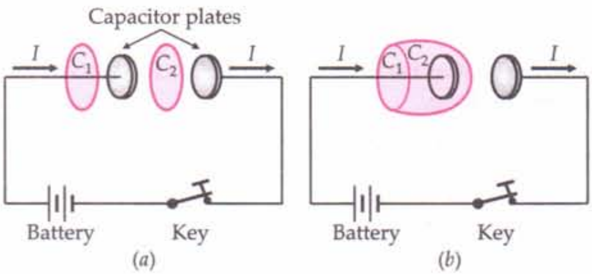

Fig. 8.1 A parallel plate capacitor being charged by a battery.

continues, a current I flows through the connecting wires, which of course changes with time. This current produces a magnetic field around the capacitor. Consider two planar loops C_1 and C_2, C_1 just left of the capacitor and C_2 in between the capacitor plates, with their planes parallel to these plates.

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

$$\oint_{C_1} \vec{B}.\vec{dl} = \mu_0 I \quad ...(2)$$

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

$$\therefore \quad \oint_{C_2} \vec{B}.\vec{dl} = 0 \quad ...(3)$$

Imagine the loops C_1 and C_2 to be infinitesimally close to each other, as shown in Fig. 8.1(*b*). Then we must have

$$\oint_{C_1} \vec{B}.\vec{dl} = \oint_{C_2} \vec{B}.\vec{dl} \quad ...(4)$$

This result is inconsistent with the equations (2) and (3). So a need for modifying Ampere's law was felt by Maxwell.

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

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

To maintain the dimensional consistency, the displacement current is given the form :

$$I_d = \varepsilon_0 \frac{d\phi_E}{dt}$$

where ϕ_E = electric field × area = EA, is the electric flux across the loop.

$\therefore$ Total current across the closed loop

$$= I_c + I_d = I_c + \varepsilon_0 \frac{d\phi_E}{dt}$$

Hence the modified form of the Ampere's law is

$$\oint \vec{B}.\vec{dl} = \mu_0 \left[I_c + \varepsilon_0 \frac{d\phi_E}{dt} \right] \quad ...(5)$$

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

$$I = I_c + I_d = I_c + \varepsilon_0 \frac{d\phi_E}{dt}$$

Consistency of modified Ampere's law. For loop C_1, there is no electric flux ($\phi_E = 0$). Therefore, from equation (5) we have

$$\oint_{C_1} \vec{B}.\vec{dl} = \mu_0 I \quad ...(6)$$

For loop C_2, conduction current $I = 0$ but $I_d \neq 0$, because a time-varying electric field exists in the region between the capacitor plates. Hence

$$\oint_{C_2} \vec{B}.\vec{dl} = \mu_0 \varepsilon_0 \frac{d\phi_E}{dt} \quad ...(7)$$

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

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

or $$EA = \frac{q}{\varepsilon_0}$$

or Flux $$\phi_E = \frac{q}{\varepsilon_0}$$

$$\therefore \quad \oint_{C_2} \vec{B}.\vec{dl} = \mu_0 \varepsilon_0 \frac{d\phi_E}{dt} = \mu_0 \varepsilon_0 \frac{d}{dt}\left(\frac{q}{\varepsilon_0}\right) = \mu_0 \frac{dq}{dt}$$

or $$\oint_{C_2} \vec{B}.\vec{dl} = \mu_0 I \qquad \left[\because I = \frac{dq}{dt}\right]$$

This agrees with the equation (6), proving the consistency of the Ampere's modified law (5).

Property of continuity. The sum $(I_c + I_d)$ has the important property of continuity along any closed path even when individually I_c and I_d may not be continuous. In Fig. 8.1, for example, a current I_c enters one plate and leaves the other plate of the capacitor. The conduction current

$$I_c = \frac{dq}{dt}$$

is not continuous across the capacitor gap as no charge is transported across this gap. The displacement current I_d is zero outside the capacitor plates and in the gap, it has the value

$$\varepsilon_0 \frac{d\phi_E}{dt} = \varepsilon_0 \frac{d}{dt}(EA) = \varepsilon_0 \frac{d}{dt}\left(\frac{q}{\varepsilon_0}\right) = \frac{dq}{dt} \qquad ...(8)$$

which is exactly the value of the conduction current in the lead wires. Thus the displacement current satisfies the basic condition that the current is continuous.

The sum $I_c + \varepsilon_0 \frac{d\phi_E}{dt}$ has the same value along the entire path (both inside and outside the capacitor plates), although individually the two currents are discontinuous. Clearly, outside the capacitor plates, we have only conduction current $I_c = I$, and there is no displacement current ($I_d = 0$). While inside the capacitor plates, there is only displacement current $I_d = I$, and there is no conduction current ($I_c = 0$). But in any general medium, both I_c and I_d are present. However, I_c is larger than I_d in a conducting medium while I_d is larger than I_c in an insulating medium.

2. *Is a displacement current associated with a magnetic field ? Or, can a changing electric flux induce a magnetic field ? Explain it with the help of an example.*

Induced magnetic field. A displacement current produces the same physical effects as the conduction current. Like a conduction current, a displacement current is also associated with a magnetic field. Consider, for example, the charging of a parallel plate capacitor by a constant current I in the connecting wires [Fig. 8.2(*a*)]. This increases the charges on the capacitor plates at a steady rate. Consequently, the electric field between the plates also increases at a steady rate. Between the capacitor plates, there exists a displacement current due to time varying electric field. In such a region, we expect a magnetic field though there is no source of conduction current nearby. Experiments have shown that a magnetic field $\vec{B}$ is

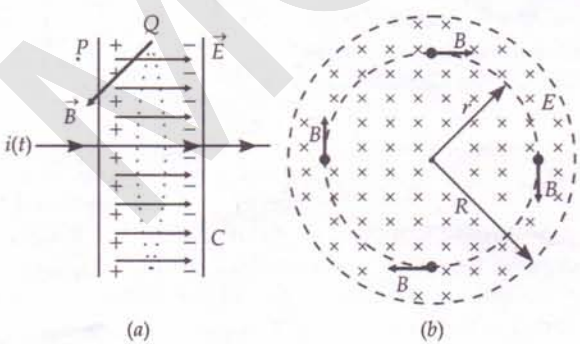

Fig. 8.2 (*a*) Electric and magnetic fields $\vec{E}$ and $\vec{B}$ at any point Q between the capacitor plates. (*b*) A cross-sectional view of Fig. 8.2(*a*)

indeed induced (say at a point Q) between the capacitor plates and has same magnitude as that just outside (say at point P).

In Fig. 8.2(*a*), the direction of $\vec{E}$ is from the positive plate to the negative, whereas the direction of $\vec{B}$ at Q is perpendicular to the plane of paper. Fig. 8.2(*b*) shows a cross-sectional loop parallel to the plane of the plates. The field $\vec{E}$ is directed normally into the plane paper, as shown by crosses. The induced field $\vec{B}$ is clockwise along the tangents on a circle in this cross-sectional plane.

3. *State the important consequences of displacement current.*

Consequences of displacement current. The concept of displacement current has made the laws of electricity and magnetism symmetrical. According to Faraday's law of electromagnetic induction, *the magnitude of induced emf is equal to the rate of change magnetic flux*. But the emf between two points is the work done in taking a unit charge from one point to another against the electrostatic forces. This implies the existence of an electric field in the region. So Faraday's law simply states that a time varying magnetic field gives rise to an electric field.

By symmetry, a time varying electric field should give rise to a magnetic field. This is an importance consequence of displacement current which is a source of magnetic field.

Another very important consequence of the symmetry of electricity and magnetism is the existence of electromagnetic waves, so important for modern communication.

4. *State the important properties of displacement current.*

Important properties of displacement current. These are as follows :

1. Displacement current exists whenever there is a change of electric flux. Unlike conduction current, it does not exist under steady conditions.
2. It is not a current. It only adds to current density in Ampere's circuital law. As it produces magnetic field, so it is called a current.
3. The magnitude of displacement current is equal to the rate of displacement of charge from one capacitor plate to the other.
4. Together with the conduction current, displacement current satisfies the property of continuity.

Examples based on

Displacement Current and Modified Ampere's Circuital Law

Formulae Used

1. Displacement current, $I_D = \varepsilon_0 \dfrac{d\phi_E}{dt}$

   Also $I_D = \varepsilon_0 \dfrac{d}{dt}(EA) = \varepsilon_0 A \dfrac{dE}{dt}$

   $$= \varepsilon_0 A \frac{d}{dt}\left(\frac{V}{d}\right) = \frac{\varepsilon_0 A}{d}\frac{dV}{dt} = C\frac{dV}{dt}$$

2. Modified Ampere's circuital law,

   $$\oint \vec{B}\,.\,\vec{dl} = \mu_0 (I_C + I_D)$$

Units Used

Electric field E is in Vm^{-1}, voltage V in volt, area A in m^2, distance d in m, current I in ampere and field B in $Wb\ m^{-2}$ or tesla.

Constants Used

Permittivity constant, $\varepsilon_0 = 8.85 \times 10^{-2} C^2 N^{-1} m^{-2}$

Permeability constant, $\mu_0 = 4\pi \times 10^{-7}\ TmA^{-1}$.

Example 1. *A parallel plate capacitor has circular plates, each of radius 5.0 cm. It is being charged so that electric field in the gap between its plates rises steadily at the rate of $10^{12}\ Vm^{-1}\ s^{-1}$. What is the displacement current ?*

Solution. Here $r = 5\text{ cm} = 5 \times 10^{-2}\text{ m}$,

$$\frac{dE}{dt} = 10^{12}\ Vm^{-1}s^{-1}$$

Displacement current,

$$I_D = \varepsilon_0 \frac{d\phi_E}{dt} = \varepsilon_0 A \frac{dE}{dt} = \varepsilon_0 \,.\, \pi r^2 \frac{dE}{dt}$$

$$= 8.85 \times 10^{-12} \times \pi \times (5 \times 10^{-2}) \times 10^{12}\ A = \mathbf{0.07\ A.}$$

Example 2. *The voltage between the plates of a parallel-plate capacitor of capacitance 1.0 μF is changing at the rate of $5\ Vs^{-1}$. What is the displacement current in the capacitor ?*

Solution. Here $C = 1.0\ \mu F = 1.0 \times 10^{-6} F$,

$$\frac{dV}{dt} = 5\ Vs^{-1}$$

Displacement current,

$$I_D = \varepsilon_0 \frac{d\phi_E}{dt} = \varepsilon_0 \frac{d}{dt}(EA) = \varepsilon_0 \frac{d}{dt}\left(\frac{VA}{d}\right)$$

$$= \frac{\varepsilon_0 A}{d}\frac{dV}{dt} = C\frac{dV}{dt}$$

$$= 1.0 \times 10^{-6} \times 5\ A = \mathbf{5.0\ \mu\ A.}$$

Example 3. *A parallel plate capacitor of area 50 cm^2 and plate separation 3.0 mm is charged initially to 80 μC. Due to radioactive source nearby, the medium between the plates gets slightly conducting and the plate loses charge initially at the rate of $1.5 \times 10^{-8}\ Cs^{-1}$. What is the magnitude and direction of displacement current ? What is the magnetic field between the plates ?*

Solution. Due to leaking, there is a flow of +ve charge from the +ve plate to the –ve plate (or the flow of –ve charge in the reverse direction). Thus the conduction current within the plates is from the +ve plate to the –ve plate. Now the displacement current is

$$I_D = \varepsilon_0 \frac{d\phi_E}{dt} = \varepsilon_0 A \frac{dE}{dt}$$

$$= \varepsilon_0 A \frac{d}{dt}\left(\frac{q}{\varepsilon_0 A}\right) = \varepsilon_0 A \frac{1}{\varepsilon_0 A}\frac{dq}{dt}$$

or $\quad I_D = \dfrac{dq}{dt} = 1.5 \times 10^{-8}\ Cs^{-1}.$

The direction of displacement current is opposite to that of electric field E and hence opposite to the conduction current. But its magnitude is same as that of the conduction current. The net current between the plates is zero.

Using Ampere's law (with I_D there replaced by $I = I_C + I_D = 0$),

$$\oint \vec{B}\,.\,\vec{dl} = \mu_0 I = \mu_0(I_C + I_D) = \mu_0 \times 0 = 0$$

So the magnetic field within the plates is zero at all points.

Example 4. *Refer to Fig. 8.3. Use modified Ampere's circuital law and the symmetry in the problem to calculate magnetic field between the plates at a point (i) on the axis (ii) 6.5 cm from the axis (iii) 15 cm from the axis. (iv) At what distance from the axis is the magnetic field due to displacement current greatest ? Obtain the maximum value of the field.*

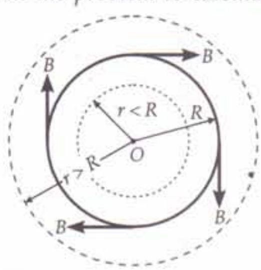

Fig. 8.3

Solution. Consider a circular loop of radius r between the plates and co-axial with them, *i.e.*, its centre lies on the axis of the plates and its plane is normal to the axis, as shown in Fig. 8.3. By symmetry, B is tangential to the circle at every point and equal in magnitude over the circle. Therefore,

$$\oint \vec{B}\,.\,\vec{dl} = B.\int_{Circle} dl = B \times 2\pi r = 2\pi r B$$

As the conduction current, $I = 0$ in the region between the plates, therefore, from modified Ampere's law

$$\oint \vec{B}.\vec{dl} = 2\pi r B = \mu_0 I_d$$

$$= \mu_0 \varepsilon_0 \times \text{Rate of change of electric flux through the area } \pi r^2.$$

When $r \le R$. Let ϕ_E be the flux through area πR^2. Then flux through area πr^2 (which is less than πR^2)

$$= \phi_E \frac{\pi r^2}{\pi R^2} = \phi_E \frac{r^2}{R^2}$$

$\therefore$ Rate of change of flux through the area πr^2

$$= \frac{d\phi_E}{dt} \cdot \frac{r^2}{R^2}$$

Hence,

$$2\pi r B = \mu_0 \varepsilon_0 \frac{d\phi_E}{dt} \cdot \frac{r^2}{R^2} = I_d \cdot \frac{r^2}{R^2}$$

$\therefore$ For $r \le R$,

$$B = \frac{\mu_0 r I_d}{2\pi R^2} \quad ...(a)$$

When $r \ge R$. In this case the capacitor plates are totally enclosed by the area πr^2 of the larger circle, so the total current through the area πr^2 is I_d. Thus

$$2\pi r B = \mu_0 I_d$$

$\therefore$ For $r \ge R$,

$$B = \frac{\mu_0 I_d}{2\pi r} \quad ...(b)$$

(*i*) From equation (*a*), the magnetic field on the axis ($r = 0$) is

$$B = 0$$

(*ii*) Here $r = 6.5$ cm and $R = 12$ cm, *i.e.*, $r < R$. Again using equation (*a*), we get

$$B = \frac{4\pi \times 10^{-7} \times 6.5 \times 10^{-2} \times 0.15}{2\pi \times (12 \times 10^{-2})^2}$$

$$= \mathbf{1.35 \times 10^{-7}\,T} \quad [I_d = 0.15 \text{ A}]$$

(*iii*) B is maximum at $r = R$. From (*a*) or (*b*), we have

$$B_{max} = \frac{\mu_0 I_d}{2\pi R} = \frac{4\pi \times 10^{-7} \times 0.15}{2\pi \times 12 \times 10^{-2}}$$

$$= \mathbf{2.5 \times 10^{-7}\ T}.$$

Example 5. *A parallel plate capacitor with circular plates of radius 1 m has a capacitance of 1 nF. At t = 0, it is connected for charging in series with a resistance R = 1 MΩ across 2 V battery. Calculate the magnetic field at a point P, in between the plates and half way between the centre and the periphery of the plates, after 10^{-3} s.* [NCERT]

Solution. Here $r = 1$ m, $C = 1\,nF = 10^{-9}$ F, $R = 1\,M\Omega = 10^6\,\Omega$, $V = 2$ V, $t = 10^{-3}$ s

Time constant of the RC circuit is

$$\tau = RC = 10^6 \times 10^{-9} = 10^{-3} \text{ s}$$

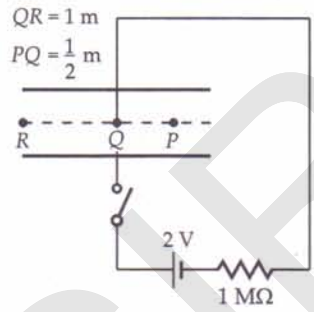

Fig. 8.4

Charge on the capacitor plate at any instant t during charging is given by

$$q(t) = CV\left[1 - e^{-\frac{t}{RC}}\right] = 10^{-9} \times 2\,[1 - e^{-\frac{t}{10^{-3}}}]$$

The electric field in between the plates at time t is

$$E = \frac{q(t)}{\varepsilon_0 A} = \frac{q(t)}{\varepsilon_0 \pi r^2} = \frac{q(t)}{\varepsilon_0 \pi} \quad ...(1)$$

Now consider a circular loop of radius 1/2 m parallel to the plates passing through P. The magnetic field B at all points on this loop is along the loop and of the same value.

The flux ϕ_E through this loop is

$$\phi_E = E \times \text{area of the loop}$$

$$= E \times \pi \times \left(\frac{1}{2}\right)^2 = \frac{\pi E}{4} = \frac{q}{4\,\varepsilon_0} \quad [\text{Using (1)}]$$

The displacement current is

$$I_d = \varepsilon_0 \frac{d\phi_E}{dt} = \varepsilon_0 \frac{d}{dt}\left(\frac{q}{4\varepsilon_0}\right)$$

$$= \frac{1}{4}\frac{dq}{dt} = \frac{1}{4}\frac{d}{dt}\left[2 \times 10^{-9}(1 - e^{-\frac{t}{10^{-3}}})\right]$$

$$= -\frac{1}{4} \times 2 \times 10^{-9} . e^{-t/10^{-3}} . \left(-\frac{1}{10^{-3}}\right)$$

$$= 0.5 \times 10^{-6} e^{-t/10^{-3}}$$

At $t = 10^{-3}$s, $I_d = 0.5 \times 10^{-6} e^{-1}$

Applying Ampere's circuital law to this loop, we get

$$B . 2\pi \times \frac{1}{2} = \mu_0 (I_c + I_d) = \mu_0 (0 + 0.5 \times 10^{-6} e^{-1})$$

$$B = \frac{\mu_0}{\pi} \times \frac{0.5 \times 10^{-6}}{e} = \frac{4\pi \times 10^{-7} \times 0.5 \times 10^{-6}}{\pi \times 2.718}$$

$$= \mathbf{0.74 \times 10^{-13}\ T}.$$

Problems For Practice

1. How would you establish a displacement current of 2.0 A in the space between the two parallel plates of $1\,\mu F$ capacitor ?*

   (Ans. By changing p.d. across the capacitor plates at the rate of $2 \times 10^6\ Vs^{-1}$)

2. A capacitor consists of two circular plates each of radius 10.0 cm and separated by 2.0 mm. The capacitor is being charged by an external battery. The charging current is constant and equal to 0.5 A. Calculate (a) the capacitance, (b) the rate of change of potential difference across the plates and (c) the displacement current.

   (Ans. 138.94 pF, $3.6 \times 10^9\ Vs^{-1}$, 0.5 A)

3. A parallel plate capacitor has two metal plates of size 30 cm × 15 cm and separated by 2.0 mm. The capacitor is being charged so that the charging current has a steady value of 100 mA. Calculate the rate of change of potential difference between the capacitor plates. What is the displacement current in the region between the capacitor plates ?

   (Ans. $5 \times 10^8\ Vs^{-1}$, 100 mA)

4. A parallel plate capacitor of capacitance $C = 0.1\,\mu F$ is connected across an a.c. source of (angular) frequency 500 rad s^{-1}. The value of conduction current is 1 mA. What is the rms value of the voltage from the source ? What is the displacement current across the capacitor plates ? (Ans. 20 V, 1 mA)

5. A parallel capacitor made of circular plates of radius 10.0 cm has a capacitance of 200 pF. The capacitor is connected to a 200 a.c. supply with an angular frequency of 200 rad s^{-1},
   (i) What is the r.m.s. value of conduction current ?
   (ii) Is the conduction current equal to displacement current ?
   (iii) Find peak value of displacement current ?
   (iv) Determine the amplitude of magnetic field at a point 2.0 cm from the axis between the plates.

   [Ans. (i) $8\,\mu A$ (ii) Yes (iii) $11.312\,\mu A$ (iv) 4.525×10^{-12} T]

HINTS

1. As proved in Example 2,

$$I_D = C\frac{dV}{dt}$$

$$\therefore \quad \frac{dV}{dt} = \frac{I_D}{C} = \frac{2.0}{10^{-6}} = \mathbf{2 \times 10^6\ Vs^{-1}}.$$

2. Proceed as in Exercise 8.1 on page 8.32.

3. $$I = \frac{dq}{dt} = \frac{d}{dt}(CV) = C\frac{dV}{dt} = \frac{\varepsilon_0 A}{d}\cdot\frac{dV}{dt}$$

$$\therefore \quad \frac{dV}{dt} = \frac{Id}{\varepsilon_0 A} = \frac{100 \times 10^{-3} \times 2 \times 10^{-3}}{8.85 \times 10^{-12} \times 0.30 \times 0.15} = \mathbf{5 \times 10^8\ Vs^{-1}}.$$

4. Here $C = 0.1\,\mu F = 10^{-7}$ F, $\omega = 500$ rad s^{-1}, $I_{rms} = 1\ mA = 10^{-3}$ A

$$V_{rms} = X_C \cdot I_{rms} = \frac{1}{\omega C}\cdot I_{rms} = \frac{1}{500 \times 10^{-7}} \times 10^{-3} = \mathbf{20\ V}.$$

5. Here $R = 10$ cm $= 0.10$ m, $C = 200$ pF $= 2 \times 10^{-10}$ F, $V_{rms} = 200$ V, $\omega = 200$ rad s^{-1}, $r = 2.0 \times 10^{-2}$ m

(i) $$I_{rms} = \frac{V_{rms}}{X_C} = \frac{V_{rms}}{1/\omega C} = \omega C V_{rms} = 200 \times 2 \times 10^{-10} \times 200 = 8 \times 10^{-6}\ A = \mathbf{8\,\mu A}.$$

(ii) Yes, because $I_D = I$

(iii) $$I_0 = \sqrt{2}\, I_{rms} = \sqrt{2} \times 8 \times 10^{-6} = 11.312 \times 10^{-6}\ A = \mathbf{11.312\,\mu A}.$$

(iv) Consider a circular loop of radius r between the plates and co-axial with them. Area of the loop, $A' = \pi r^2$. By symmetry, B is tangential to the circle at every point and is equal in magnitude over the circle. Here only a part of the displacement current I_D threads the loop of area A'.

$\therefore$ Current through area A'

$$= \frac{I_D}{\pi R^2} \times \pi r^2 = \frac{r^2}{R^2}\cdot I_D$$

Using modified Ampere's circuital law,

$$\oint \vec{B} \cdot \vec{dl} = \mu_0 \times \text{Current through area } A'$$

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

$$B = \frac{\mu_0 I_D r}{2\pi R^2} = \frac{4\pi \times 10^{-7} \times 11.312 \times 10^{-6} \times 2 \times 10^{-2}}{2\pi \times (0.1)^2} = \mathbf{4.525 \times 10^{-12}\ T}.$$

8.3 MAXWELL'S EQUATIONS

Maxwell found that all the basic principles of electromagnetism can be formulated in terms of four fundamental equations called Maxwell's equations. Assuming that no magnetic or dielectric material is present, the four basic equations can be stated as follows :

1. Gauss law of electrostatics. This law states that the *electric flux through a closed surface S is* $\frac{1}{\varepsilon_0}$ *times the total charge q enclosed by the surface S.*

i.e., $$\oint_S \vec{E} \cdot d\vec{S} = \frac{q}{\varepsilon_0} \quad ...(9)$$

Important consequences of this law are that (*i*) the charge on an insulated conductor resides only on its outer surface, and (*ii*) the electrostatic force between two charges is inversely proportional to the square of the distance between them.

2. Gauss law of magnetism. According to this law, the magnetic flux through any closed surface is always zero.

i.e., $$\oint_S \vec{B} \cdot d\vec{S} = 0 \quad ...(10)$$

This law implies that isolated magnetic poles or magnetic charges do not exist, *i.e.,* it explains the absence of magnetic monopoles.

3. Faraday's law of electromagnetic induction. This law tells that a changing magnetic field induces an electric field. According to this law, the induced emf set up in a closed circuit C is equal to the rate of change of magnetic flux linked with the closed circuit.

i.e., $$\oint_C \vec{E} \cdot d\vec{l} = -\frac{d\phi_B}{dt}$$

or $$\varepsilon = -\frac{d}{dt}\left[\oint_C \vec{B} \cdot d\vec{S}\right] \quad ...(11)$$

4. Modified Ampere's law. This law states that the line integral of the magnetic field around any closed circuit C is equal to μ_0 times the total current (the sum of conduction and displacement currents) threading the closed circuit.

i.e., $$\oint_C \vec{B} \cdot d\vec{l} = \mu_0[I_c + I_d] = \mu_0\left[I_c + \varepsilon_0 \frac{d\phi_E}{dt}\right] \quad ...(12)$$

This law implies the fact that not only a conduction current but a displacement current, associated with a changing electric field, also produces a magnetic field.

8.4 MAXWELL'S PREDICTION OF ELECTROMAGNETIC WAVES

5. *Explain clearly how Maxwell was led to predict the existence of electromagnetic waves. How can these waves be represented mathematically ?*

Maxwell's prediction of electromagnetic waves. In 1865, Maxwell theoretically predicted the existence of electromagnetic waves. According to Faraday's law of electromagnetic induction :

A time-varying magnetic field is a source of changing electric field.

On the basis of his theoretical studies, Maxwell argued that

A time-varying electric field is a source of changing magnetic field.

This means that the change in either field (electric/magnetic) produces the other field. Maxwell further showed that these variations in electric and magnetic fields occur in mutually perpendicular directions and have wave like properties. He was thus led to the idea that a wave of electric and magnetic fields both varying with space and time should exist, one providing the source of the other. Such a wave is called an ***electromagnetic wave*** and it indeed exists.

An electromagnetic wave is a wave radiated by an accelerated charge and which propagates through space as coupled electric and magnetic fields, oscillating perpendicular to each other and to the direction of propagation of the wave.

Mathematical representation of electromagnetic waves. Figure 8.5 shows a plane electromagnetic wave travelling along X-axis. The electric field $\vec{E}$ oscillates along Y-axis while the magnetic field $\vec{B}$ oscillates along Z-axis.

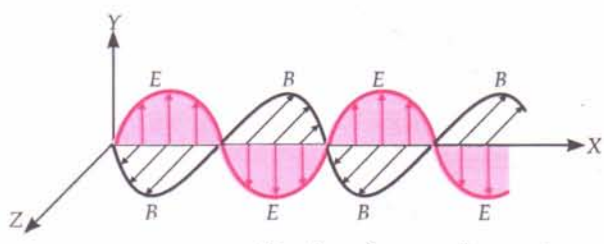

Fig. 8.5 A plane electromagnetic wave travelling along X-axis.

The values of electric and magnetic fields shown in the above figure depend only on x and t. The electric field vector can be represented mathematically as follows :

$$\vec{E} = E_y\,\hat{j} = E_0 \sin(kx - \omega t)\,\hat{j}$$
$$= E_0 \sin\left[2\pi\left(\frac{x}{\lambda} - \nu t\right)\right]\hat{j}$$
$$= E_0 \sin\left[2\pi\left(\frac{x}{\lambda} - \frac{t}{T}\right)\right]\hat{j} \qquad ...(1)$$

where $k = 2\pi/\lambda$ is the propagation constant of the wave and angular frequency, $\omega = 2\pi\nu$.

Clearly, $E_x = E_z = 0$

The magnetic field vector may be represented as

$$\vec{B} = B_z\,\hat{k} = B_0 \sin(kx - \omega t)\,\hat{k}$$
$$= B_0 \sin\left[2\pi\left(\frac{x}{\lambda} - \nu t\right)\right]\hat{k}$$
$$= B_0 \sin\left[2\pi\left(\frac{x}{\lambda} - \frac{t}{T}\right)\right]\hat{k} \qquad ...(2)$$

Clearly, $B_x = B_y = 0$.

Here E_0 and B_0 are the *amplitudes* of the electric field $\vec{E}$ and magnetic field $\vec{B}$, respectively.

Equations (1) and (2) show that the *variations in electric and magnetic fields are in same phase, i.e.,* both attain their maxima and minima at the same instant and at the same place (x).

The magnitudes of $\vec{E}$ and $\vec{B}$ are related as

$$\frac{E}{B} = c \quad \text{or} \quad \frac{E_0}{B_0} = c$$

Maxwell also showed that the speed of an e.m. wave depends on the permeability and permittivity of the medium through which it travels. The speed of an e.m. wave in free space is given by

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

Permeability of free space,

$$\mu_0 = 4\pi \times 10^{-7}\ \text{Ns}^2\ \text{C}^{-2}$$

Permittivity of free space,

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

$$\therefore \quad c = \frac{1}{\sqrt{4\pi \times 10^{-7} \times 8.85 \times 10^{-12}}}$$
$$= \mathbf{3.0 \times 10^8\ ms^{-1}}$$

which is the speed of light in vacuum. This fact led Maxwell to predict that light is an electromagnetic wave. The emergence of the speed of light from purely electromagnetic considerations is the crowning achievement of Maxwell's electromagnetic theory.

The speed of an e.m. wave in any medium of permeability μ and permittivity ε will be

$$v = \frac{1}{\sqrt{\varepsilon\mu}} = \frac{1}{\sqrt{\kappa\,\varepsilon_0\,\mu_r\,\mu_0}} = \frac{c}{\sqrt{\kappa\,\mu_r}}$$

where κ is the dielectric constant of the medium and μ_r is its relative permeability.

As the electric and magnetic fields in an e.m. wave are always perpendicular to each other and also perpendicular to the direction of wave propagation, so e.m. waves are transverse in nature.

8.5 SOURCES OF ELECTROMAGNETIC WAVES

6. *Briefly explain how is an accelerating charge a source of an electromagnetic wave.*

An accelerating charge as a source of an electromagnetic wave. A stationary charge produces only an electrostatic field while a charge in uniform motion produces a magnetic field that does not change with time. Thus, neither stationary charges nor charges in uniform motion (or steady currents) can produce electromagnetic waves. According to Maxwell, *an accelerating charge produces electromagnetic waves.* Consider a charge oscillating harmonically with time. This is an example of an accelerating charge. This charge produces an oscillating electric field in its neighbourhood. This field, in turn, produces an oscillating magnetic in the neighbourhood. The process continues because the oscillating electric and magnetic fields act as sources of each other. Hence an electromagnetic wave originates from the oscillating charge. *The frequency of the electromagnetic wave is equal to the frequency of oscillation of the charge.* The energy carried by the wave comes from the source which makes the charge oscillating.

From the above discussion, we may note that in order to generate an electromagnetic wave of frequency ν, we need to set up an a.c. circuit in which the current oscillates at the frequency ν. Hence it is easier to generate low frequency e.m. waves, such as a radiowave. However, it is not possible to experimentally demonstrate the existence of high frequency e.m. waves, such as visible light. For example, the generation of yellow light requires an oscillator of frequency 6×10^{14} Hz, while the modern oscillators have frequency hardly above 10^{11} Hz.

In the next section, we discuss Hertz's experiment for demonstrating the existence of low frequency radiowaves.

8.6 HERTZ'S EXPERIMENT

7. *Describe Hertz's experiment for producing and detecting electromagnetic waves. How were the various properties of electromagnetic waves demonstrated by Hertz ?*

Hertz's experiment. Maxwell predicted the existence of electromagnetic waves in 1865. This prediction had to wait for about 22 years before a German physicist, *Heinrich Hertz,* succeeded in experimentally confirming the existence of electromagnetic waves in 1887.

In the oscillations of an *LC*- circuit, we know that the charge oscillates across the capacitor plates. Since an oscillating charge has non-zero acceleration, it will continuously emit electromagnetic waves. As shown in Fig. 8.6, *Hertz* used an oscillatory *LC*-circuit for producing electromagnetic waves.

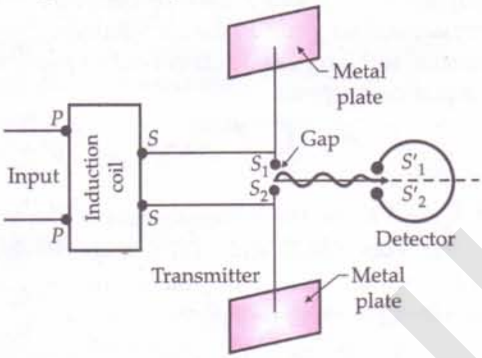

Fig. 8.6 Hertz's experimental set-up for producing and detecting e.m. waves.

The ***transmitter*** consists of two large square metal (brass) plates with sides of length 40 cm. These are placed in the same vertical plane with their centres about 60 cm apart. The plates are connected to two thick wires ending in highly polished brass spheres S_1 and S_2. The distance between the two spheres is 2 to 3 cm. The two thick wires are connected to the secondary terminals of an induction coil.

Every time the current in the primary circuit of the induction coil is interrupted, a large p.d. is set up across S_1 and S_2 and the metal plates get charged. The high p.d. ionises the air in the gap and makes the gap conducting. The electrons and ions so produced oscillate back and forth across the gap S_1S_2. An oscillatory discharge of the plates occurs through the conducting gap. The process results in the production of e.m. waves.

The metal plates form a capacitor of low capacitance *C* and connecting wires offer a low inductance *L* The system generates e.m. waves of high frequency (ν) given by

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

The ***receiver*** or ***detector*** consists of an almost closed circular stout wire terminating at the two ends in two small polished brass spheres S'_1 and S'_2. The electromagnetic waves reaching the gap of the detector are associated with a sufficiently strong electric field which sets up a high p.d. across the gap $S'_1 S'_2$. This causes tiny sparks jumping across the gap, thereby proving the existence of e.m. waves.

Hertz demonstrated the various properties of e.m. waves as follows :

1. Hertz observed that maximum sparks are produced across the detector gap when this gap is parallel to the transmitter gap. When these two gaps are perpendicular to each other, no sparkes are produced across the detector gap *i.e.,* no electromagnetic waves are detected. This means that electric field associated with the waves radiated from the transmitter is parallel to the two gaps *i.e.,* the direction of the electric field is perpendicular to the direction of propagation of the e.m. wave. This clearly demonstrates that the ***e.m. waves are transverse in nature.***

2. Hertz not only produced and detected electromagnetic waves, but also demonstrated their properties of reflection, refraction and interference and so established beyond doubt that the ***e.m. radiation has a wave nature.***

3. Hertz allowed the e.m. waves to fall on a large plane sheet of zinc. The reflected waves superimposed on the incident waves, produced stationary e.m. waves. The wavelength of these waves was determined by measuring the distance between two nodes. The frequency of the wave was equal to that of the oscillator, *i.e.,*

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

Hence the speed of the e.m. wave was determined by using the formula $v = \nu\lambda$. It was found that ***e.m. waves travel with the same speed as the speed of light.***

4. *Electromagnetic waves can be polarised.* To test this fact, take a portable AM radio provided with a telescopic antenna. It responds to the electric component of the e.m. signal from the broadcasting station. When the antenna is turned horizontal, the signal is greatly diminished. The portable radios having horizontal antenna inside them are sensitive to the magnetic component of e.m. wave. The signal is best received when such a radio is held horizontal.

In Hertz set-up, the frequency of the e.m. waves produced was 5×10^7 Hz. So the wave length of the e.m. waves produced is given by

$$\lambda = \frac{c}{\nu} = \frac{3 \times 10^8}{5 \times 10^7} = 6 \text{ m.}$$

8.7 HISTORY OF THE OBSERVATION OF EM WAVES

8. *Give a brief history of the observation of electromagnetic waves.*

History of the observation of electromagnetic waves. In 1865, ***Maxwell*** predicted the existence of electromagnetic waves purely from theoretical considerations. He showed that an accelerating charge produces electromagnetic waves. Since an oscillating charge is accelerated continuously, it would continuously produce e.m. waves of same frequency as that of the oscillating charge.

In 1887, ***Hertz*** succeeded in experimentally confirming the existence of e.m. waves. He used an oscillatory *LC*-circuit for producing these waves. He was able to produce and detect e.m. waves of wavelength around 6 m.

In 1885, ***Sir J.C. Bose*** succeeded in producing e.m. of much shorter wavelength (5 mm to 25 mm) with the help of a self-designed radiator. He was able to transmit e.m. waves over a distance of about 20 m.

In 1896, ***Guglielmo Marconi***, discovered that if one of the spark gap terminals is connected to antenna and the other terminal is earthed, then e.m. waves can be transmitted over distances of several kilometers. He succeeded in transmitting e.m. waves across the British Channel in 1899 and across the Atlantic Ocean in 1901. His experiments marked the beginning of radio communication.

8.8 TRANSVERSE NATURE OF ELECTROMAGNETIC WAVES

9. *Prove mathematically that electromagnetic waves are transverse in nature.*

Transverse nature of electromagnetic waves. Consider a plane electromagnetic wave travelling in the *X*-direction. The associated wavefront lies in the *YZ*-plane (a wavefront is the locus of continuous points having same phase of vibration) and *ABCD* is a portion of it at any time *t*. The electric and magnetic fields at time *t* will be zero to the right of *ABCD*. To the left of *ABCD*, they depend on *x* and *t*, but not on *y* and *z*, as we are considering only a plane wave.

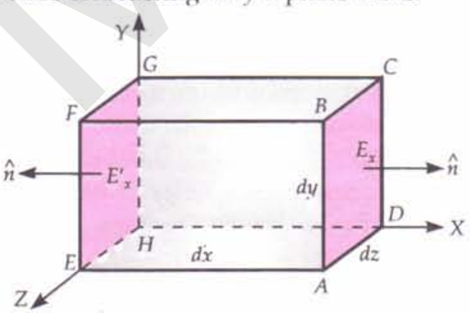

Fig. 8.7 Elementary parallelopiped *ABCDEFGH* chosen as a closed surface.

We use Gauss's law to prove the transverse nature of electromagnetic waves. Consider the closed surface enclosed by the parallelopiped *ABCDEFGH* of sides *dx*, *dy* and *dz*. The total electric flux through this closed surface must be zero as it does not enclose any charge. Hence

$$\oint_{ABCDEFGH} \vec{E}.d\vec{S} = 0$$

or $$\left[\int_{ABCD} \vec{E}.d\vec{S} + \int_{EFGH} \vec{E}.d\vec{S}\right] + \left[\int_{ABFE} \vec{E}.d\vec{S} + \int_{DCGH} \vec{E}.d\vec{S}\right] + \left[\int_{AEHD} \vec{E}.d\vec{S} + \int_{BFGC} \vec{E}.d\vec{S}\right] = 0$$

The paired integrals are the contributions from the faces normal to *X*, *Y* and *Z*-axis, respectively. Since *E* does not depend on *y* and *z*, the contributions from the faces normal to *Y* and *Z*-axis cancel out in pairs, so the above equation becomes

$$\int_{ABCD} \vec{E}.d\vec{S} + \int_{EFGH} \vec{E}.d\vec{S} = 0 \qquad ...(1)$$

Let E_x and E'_x be the *x* components of the electric field at the faces *ABCD* and *EFGH*, respectively. The outward normals on these faces are oppositely directed (along *X*-axis), therefore,

$$\int_{ABCD} \vec{E}.d\vec{S} = E_x \,.\, dy\, dz$$

$$\int_{EFGH} \vec{E}.d\vec{S} = -E'_x \, dy\, dz$$

Hence equation (1) becomes

$$E_x \,.\, dy\, dz - E'_x . dy\, dz = 0 \quad \text{or} \quad E_x = E'_x$$

i.e., the component of the electric field along the direction of propagation is constant. But a constant or static field cannot produce a wave, so this constant must be equal to zero, *i.e.*, $E_x = 0$

Similarly, we can prove that $B_x = 0$. Thus the electric or magnetic fields have no component along the direction of propagation. Or, *in an electromagnetic wave both the electric and magnetic fields are perpendicular to the direction of propagation, i.e., the electromagnetic waves are transverse in nature.*

8.9 ENERGY DENSITY, INTENSITY AND MOMENTUM OF ELECTROMAGNETIC WAVES

10. *Obtain expression for the energy density of an electromagnetic wave. In an electromagnetic wave, show that the average energy density of the E field equals the average energy density of the B field.*

Energy density of an electromagnetic wave. Electromagnetic waves carry energy as they travel through space and this energy is shared equally by the electric and magnetic fields. ***Energy density*** *of an e.m. wave is the energy in unit volume of the space through which the wave travels.*

We know that energy is stored in space wherever electric and magnetic fields are present.

In free space, the energy density of a static field E is

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

Again in free space, the energy density of a static magnetic field is

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

The total energy density of the static electric and magnetic fields will be

$$u = u_E + u_B = \frac{1}{2}\varepsilon_0 E^2 + \frac{1}{2\mu_0} B^2$$

But in an electromagnetic wave, both E and B fields vary sinusoidally in space and time. The average energy density u of an e.m. wave can be obtained by replacing E and B by their rms values in the above equation. Thus

$$u = \frac{1}{2}\varepsilon_0 E_{rms}^2 + \frac{1}{2\mu_0} B_{rms}^2$$

or $$u = \frac{1}{4}\varepsilon_0 E_0^2 + \frac{1}{4\mu_0} B_0^2 \quad \left[\because E_{rms} = \frac{E_0}{\sqrt{2}}, B_{rms} = \frac{B_0}{\sqrt{2}}\right]$$

Moreover, $E_0 = cB_0$ and $c^2 = \frac{1}{\mu_0 \varepsilon_0}$, therefore

$$u_E = \frac{1}{4}\varepsilon_0 E_0^2 = \frac{1}{4}\varepsilon_0 (cB_0)^2$$

$$= \frac{1}{4}\varepsilon_0 \cdot \frac{B_0^2}{\mu_0 \varepsilon_0} = \frac{1}{4\mu_0} B_0^2 = u_B$$

Hence *in an electromagnetic wave, the average energy of the E field equals the average energy density of the B field.*

It may be noted that

$$u = \frac{1}{4}\varepsilon_0 E_0^2 + \frac{1}{4}\varepsilon_0 E_0^2 = \frac{1}{2}\varepsilon_0 E_0^2 = \varepsilon_0 E_{rms}^2$$

Also,

$$u = \frac{1}{4\mu_0} B_0^2 + \frac{1}{4\mu_0} B_0^2 = \frac{1}{2\mu_0} B_0^2 = \frac{1}{\mu_0} B_{rms}^2$$

11. *Define intensity of an electromagnetic wave. Obtain an expression for it.*

Intensity of an electromagnetic wave. *The energy crossing per unit area per unit time in a direction perpendicular to the direction of propagation is called intensity of the wave.*

Suppose a plane electromagnetic wave propagates along X-axis with speed c. As shown in Fig. 8.8, consider a cylindrical volume with area of cross-section A and length $c\,\Delta t$ along the X-axis. The energy

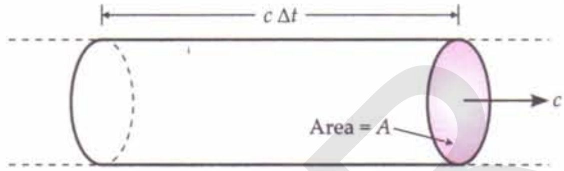

Fig. 8.8 Calculation of intensity.

contained in this cylinder crosses the area A in time Δt as the wave propagates with speed c. The energy contained is

$$U = \text{Average energy density} \times \text{volume}$$

$$= u \times c\,\Delta t \times A$$

Intensity of the wave,

$$I = \frac{\text{Energy}}{\text{Area} \times \text{Time}} = \frac{U}{A\,\Delta t} = uc$$

or $$I = \frac{1}{2}\varepsilon_0 E_0^2 c = \varepsilon_0 E_{rms}^2 c$$

Also, $$I = \frac{1}{2\mu_0} B_0^2 c = \frac{1}{\mu_0} B_{rms}^2 c$$

Thus *the intensity of an electromagnetic wave is proportional to the square of the electric/magnetic field.* Conversely, the size of the electric/magnetic field of an electromagnetic wave is proportional to the square root of its intensity.

12. *Write an expression for the momentum carried by an e.m. wave.*

Momentum of an e.m. wave. An electromagnetic wave transports linear momentum as it travels through space. If an electromagnetic wave transfers a total energy U to a surface in time t, then total linear momentum delivered to the surface is

$$p = \frac{U}{c}$$

[For complete absorption of energy U]

If the wave is totally reflected, the momentum delivered will be $2U/c$, because the momentum of the wave will change from p to $-p$.

13. *Write an expression for the pressure exerted by an electromagnetic wave.*

Pressure exerted by an e.m. wave. *When an electromagnetic wave falls on a surface, it exerts pressure on the surface.*

This pressure is called ***radiation pressure***. The radiation pressure for an electromagnetic wave of intensity I is given by

$$P_r = \frac{I}{c}$$

It is because of the radiation pressure of the solar radiation that the tails of comets point away from the sun.

8.10 PROPERTIES OF ELECTROMAGNETIC WAVES

14. *Mention the various properties of electromagnetic waves.*

Properties of electromagnetic waves. These are as follows :

1. The electromagnetic waves are produced by accelerated charges and do not require any material medium for their propagation.
2. The directions of oscillations of $\vec{E}$ and $\vec{B}$ fields are perpendicular to each other as well as perpendicular to the direction of propagation of the wave. So the electromagnetic waves are transverse in nature.
3. The oscillations of $\vec{E}$ and $\vec{B}$ fields are in same phase.
4. All electromagnetic waves travel in free space with the same speed,
$$c = \frac{1}{\sqrt{\mu_0 \varepsilon_0}} \simeq 3 \times 10^8 \text{ ms}^{-1}$$
In a material medium, the electromagnetic waves travel with the speed,
$$v = \frac{1}{\sqrt{\mu \varepsilon}} = \frac{c}{\sqrt{\mu_r \varepsilon_r}} = \frac{c}{n}$$
where n is the refractive index of the medium.
5. The amplitude ratio of the electric and magnetic fields is $\frac{E_0}{B_0} = c = \frac{1}{\sqrt{\mu_0 \varepsilon_0}}$
6. The electromagnetic waves carry energy as they travel through space and this energy is shared equally by the electric and magnetic fields. The average energy density of an e.m. wave is
$$u = u_E + u_B = \frac{1}{2}\left[\varepsilon_0 E_0^2 + \frac{B_0^2}{\mu_0}\right]$$
7. Electromagnetic waves transport linear momentum as they travel through space :
$$p = \frac{U}{c}.$$
8. Electromagnetic waves are not deflected by electric and magnetic fields.
9. Electromagnetic waves obey the principle of superposition. They show the properties of reflection, refraction, interference, diffraction and polarisation.
10. The electric field of an electromagnetic wave is responsible for its optical effects, because $E_0 >> B_0$.

For Your Knowledge

- An accelerating or oscillating charge is a source of electromagnetic waves. An electric charge oscillating harmonically with frequency ν, produces electromagnetic waves of frequency ν. An oscillating electric dipole radiates electromagnetic waves.
- All types of electromagnetic waves travel through vacuum with the same speed but they travel with different speeds in any material medium.
- The frequency of an electromagnetic wave is its inherent characteristic. When an electromagnetic wave travels from one medium to another, its wavelength changes but frequency remains unchanged.
- The ratio ω / c gives the magnitude of the propagation vector $\vec{k}$ for an electromagnetic wave,
$$k = \frac{2\pi}{\lambda} = \frac{\omega}{c}$$
- The direction of propagation of an electromagnetic wave is same as that of the vector $\vec{E} \times \vec{B}$.
- The speed of an electromagnetic wave through any medium depends on its permeability μ and permittivity ε.
$$v = \frac{1}{\sqrt{\mu\, \varepsilon}} = \frac{c}{\sqrt{\mu_r\, \varepsilon_r}}$$
- Half of the intensity of an electromagnetic wave is provided by its electric field and half by the magnetic field. So the power delivered by the magnetic field of an electromagnetic wave is equal to the power delivered by its electric field, but the magnetic field strength is much weaker than the electric field strength. In fact,
$$\frac{E_0}{B_0} = c$$
- The fact that electromagnetic waves can carry energy from one place to another, is of great technical importance. They transmit energy from radio and TV stations to our homes. Light carries energy from the sun to the earth, thus making life possible on the earth.
- In 1903, the American scientists *Nicols* and *Hull* successfully measured the radiation pressure of visible light and found it to be of the order of 7×10^{-6} Nm^{-2}. Thus, on a surface area of 10 cm^2, the force due to radiation is only about 7×10^{-9} N.

Examples based on
Equation, Speed, Amplitude and Average Density of an Electromagnetic Wave

Formulae Used

1. Wave velocity, $c = \nu\lambda$
2. Energy of photon, $E = h\nu = \frac{hc}{\lambda}$
3. Speed of e.m. wave in vacuum, $c = \frac{1}{\sqrt{\mu_0 \varepsilon_0}}$
4. Speed of e.m. wave in a material medium, $c = \frac{1}{\sqrt{\mu\varepsilon}}$
5. For a wave of frequency ν, wavelength λ, propagating along x-direction, the equations for electric and magnetic fields are
$$E_y = E_0 \sin(kx - \omega t) = E_0 \sin\left[2\pi\left(\frac{x}{\lambda} - \frac{t}{T}\right)\right]$$
$$B_z = B_0 \sin(kx - \omega t) = B_0 \sin\left[2\pi\left(\frac{x}{\lambda} - \frac{t}{T}\right)\right]$$
6. Amplitude ratio of electric and magnetic fields,
$$\frac{E_0}{B_0} = c = \frac{1}{\sqrt{\mu_0 \varepsilon_0}}$$
7. Propagation constant, $k = \frac{2\pi}{\lambda} = \frac{\omega}{c}$
8. Average energy density of E-field,
$$u_E = \frac{1}{4}\varepsilon_0 E_0^2 = \frac{1}{2}\varepsilon_0 E_{rms}^2$$
9. Average energy density of B-field,
$$u_B = \frac{1}{4\mu_0} B_0^2 = \frac{1}{2\mu_0} B_{rms}^2$$
10. Average energy density of e.m. wave,
$$u_{av} = \frac{1}{2}\varepsilon_0 E_{rms}^2 + \frac{1}{2\mu_0} B_{rms}^2 = \varepsilon_0 E_{rms}^2 = \frac{B_{rms}^2}{\mu_0}$$
or $$u_{av} = \frac{1}{4}\varepsilon_0 E_0^2 + \frac{1}{4\mu_0} B_0^2 = \frac{1}{2}\varepsilon_0 E_0^2 = \frac{1}{2\mu_0} B_0^2$$
11. Momentum delivered by an e.m. wave.
$$p = \frac{U}{c}$$
12. Intensity of a wave $= \frac{\text{Energy / time}}{\text{Area}} = \frac{\text{Power}}{\text{Area}}$

or $I = u_{av}\, c = \varepsilon_0 E_{rms}^2\, c.$

Units Used

Wave velocity c is in ms^{-1}, wavelength λ in metre, frequency ν in Hz, field E in Vm^{-1}, field B in tesla, energy densities u_E, u_B and u_{av} are in Jm^{-3}, intensity I in Wm^{-2}.

Example 6. *Electromagnetic waves travel in a medium at a speed of $2.0 \times 10^8\ ms^{-1}$. The relative permeability of the medium is 1.0. Find the relative permittivity.*

Solution. Speed of an e.m. wave in a medium is given by

$$v = \frac{1}{\sqrt{\mu\,\varepsilon}} = \frac{1}{\sqrt{\mu_r \mu_0\, \varepsilon_r\, \varepsilon_0}}$$
$$= \frac{1}{\sqrt{\mu_0 \varepsilon_0}} \frac{1}{\sqrt{\mu_r\, \varepsilon_r}} = \frac{c}{\sqrt{\mu_r \varepsilon_r}}$$
$$\therefore \quad v^2 = \frac{c^2}{\mu_r\, \varepsilon_r}$$

Hence relative permittivity,

$$\varepsilon_r = \frac{c^2}{\mu_r v^2} = \frac{(3 \times 10^8)^2}{1.0 \times (2 \times 10^8)^2} = \mathbf{2.25.}$$

Example 7. *A plane electromagnetic wave of frequency 25 MHz travels in free space along the x-direction. At a particular point in space and time, $\vec{E} = 6.3\,\hat{j}\ Vm^{-1}$. What is $\vec{B}$ at this point ?* [NCERT ; CBSE D 06C]

Solution. Magnitude of $\vec{E}$, $E = 6.3\ Vm^{-1}$

Magnitude of $\vec{B}$,

$$B = \frac{E}{c} = \frac{6.3\ Vm^{-1}}{3 \times 10^8\ ms^{-1}} = 2.18 \times 10^{-8} T$$

We note that $\vec{E}$ is along y-direction and the wave propagates along x-direction. Now an e.m. wave propagates in the direction of the vector $\vec{E} \times \vec{B}$. So this vector must point along x-direction. As

$$(+\hat{j}) \times (+\hat{k}) = +\hat{i}$$

Clearly, vector $\vec{B}$ is along z-direction. We can write

$$\vec{B} = \mathbf{2.18 \times 10^{-8}\, \hat{k}\ T.}$$

Example 8. *The magnetic field in a plane electromagnetic wave is given by*

$$B_y = 2 \times 10^{-7} \sin(0.5 \times 10^3 x + 1.5 \times 10^{11}\, t)\, T.$$

(a) What is the wavelength and frequency of the wave ?
(b) Write an expression for the electric field. [NCERT]

Solution. Given

$B_y = 2 \times 10^{-7} \sin(0.5 \times 10^3 x + 1.5 + 10^{11} t)$ tesla

On comparing with the standard equation,

$$B_y = B_0 \sin\left[2\pi\left(\frac{x}{\lambda} - \nu t\right)\right]$$

we get, $\frac{2\pi}{\lambda} = 0.5 \times 10^3$

$\therefore$ Wavelength,

$$\lambda = \frac{2\pi}{0.5\times10^3} = \frac{2\times3.14}{0.5\times10^3}$$

$$= 1.26\times10^{-2}\text{m} = \mathbf{1.26\ cm.}$$

Also, $2\pi\nu = 1.5\times10^{11}$

$$\therefore \quad \nu = \frac{1.5\times10^{11}}{2\pi} = \frac{1.5\times10^{11}}{2\times3.14}$$

$$= 23.9\times10^9\ \text{Hz} = \mathbf{23.9\ GHz.}$$

(*b*) $B_0 = 2\times10^{-7}$ T

$\therefore\ E_0 = cB_0 = 3\times10^8\times2\times10^{-7} = 60\ \text{Vm}^{-1}$

The electric field is perpendicular to the direction of propagation (x-axis) and the direction of magnetic field (y-axis). So the expression for electric field is

$$E_z = 60\sin(0.5\times10^3 x + 1.5\times10^{11}\ t)\ \text{Vm}^{-1}.$$

EXAMPLE 9. *Light with an energy flux of 18 watts / cm² falls on a non-reflecting surface at normal incidence. If the surface has an area of 20 cm², find the average force exerted on the surface during a 30 minute time span.* **[NCERT]**

Solution. Energy flux

$$= 18\ \text{W cm}^{-2} = 18\ \text{Js}^{-1}\text{cm}^{-2}$$

Area = 20 cm²

Time = 30 min = 1800 s

Total energy falling on the surface

$$U = \text{Energy flux}\times\text{time}\times\text{area}$$

$$= (18\ \text{Js}^{-1}\text{cm}^{-2})\times1800\ \text{s}\times20\ \text{cm}^2$$

$$= 6.48\times10^5\ \text{J}$$

The total momentum delivered to the surface,

$$p = \frac{U}{c} = \frac{6.48\times10^5\ \text{J}}{3\times10^8\ \text{ms}^{-1}}$$

$$= 2.16\times10^{-3}\text{kgms}^{-1}$$

The average force exerted on the surface,

$$F = \frac{p}{t} = \frac{2.16\times10^{-3}}{1800} = \mathbf{1.2\times10^{-6}\ N}$$

In case, the surface is a perfect reflector, the change of momentum

$$= p-(-p) = 2p$$

and $F = 2\times1.2\times10^{-6} = \mathbf{2.4\times10^{-6}N.}$

Example 10. *Calculate the electric and magnetic fields produced by the radiation coming from a 100 watt bulb at a distance of 3 m. Assume that the efficiency of the bulb is 2.5% and it is a point source.* [NCERT]

Solution. The bulb, as a point source, radiates light in all directions uniformly. At a distance of 3 m, the surface area of the surrounding sphere is

$$A = 4\pi r^2 = 4\pi(3)^2 = 113\ \text{m}^2$$

The intensity at this distance is

$$I = \frac{\text{Power}}{\text{Area}} = \frac{2.5\%\text{ of }100\text{ W}}{113\text{ m}^2}$$

$$= 0.022\ \text{Wm}^{-2}$$

Half of this intensity is provided by the electric field and half by the magnetic field.

But intensity of e.m. wave

$$= \varepsilon_0 E_{rms}^2 c$$

$$\frac{1}{2}I = \frac{1}{2}\varepsilon_0 E_{rms}^2 c = \frac{1}{2}\times0.002\ \text{Wm}^{-2}.$$

or $$E_{rms}^2 = \frac{0.022}{\varepsilon_0 c} = \frac{0.022}{8.85\times10^{-12}\times3\times10^8} = 8.286$$

or $$E_{rms} = 2.878 \simeq \mathbf{2.9\ Vm^{-1}}$$

Peak value,

$$E_0 = \sqrt{2}\ E_{rms} = 1.414\times2.9 = \mathbf{4.1\ Vm^{-1}}$$

The strength of the magnetic field,

$$B_{rms} = \frac{E_{rms}}{c} = \frac{2.9\ \text{Vm}^{-1}}{3\times10^8\ \text{ms}^{-1}} = \mathbf{9.6\times10^{-8}\ T}$$

Also, $$B_0 = \sqrt{2}\ B_{rms} = 1.414\times9.6\times10^{-8}$$

$$= \mathbf{1.4\times10^{-7}\ T.}$$

It may be noted that although the power in the magnetic field is equal to the power in the electric field, yet the magnetic field strength is very weak.

Example 11. *A plane electromagnetic wave in the visible region is moving along the z-direction. The frequency of the wave is 0.5×10^{15} Hz and the electric field at any point is varying sinusoidally with time with an amplitude of 1 Vm^{-1}. Calculate the average values of the densities of the electric and the magnetic fields.*

Solution. Average energy density of the electric field is

$$u_E = \frac{1}{4}\varepsilon_0 E_0^2 = \frac{1}{4}\times8.85\times10^{-12}\times1^2$$

$$= \mathbf{2.21\times10^{-12}\ Jm^{-3}}$$

Average energy density of the magnetic field is

$$u_B = \frac{B_0^2}{4\mu_0} = \frac{1}{4}\frac{E_0^2}{\mu_0 c^2} \qquad \left[\because\ B_0 = \frac{E_0}{c}\right]$$

$$= \frac{1}{4}\times\frac{1^2}{4\pi\times10^{-7}}\times\frac{1}{(3\times10^8)^2}$$

$$= \mathbf{2.21\times10^{-12}\ Jm^{-3}}.$$

Example 12. *The electric field in an e.m. wave is given by*

$$E = 50\sin\frac{2\pi}{\lambda}(ct-x)\ \text{NC}^{-1}$$

Find the energy contained in a cylinder of cross-section 10 cm² and length 50 cm along the x-axis.

Solution. Here $E_0 = 50\ NC^{-1}$

$\therefore$ Average energy density of the e.m. wave is

$$u_{av} = \frac{1}{2}\varepsilon_0 E_0^2 = \frac{1}{2} \times 8.55 \times 10^{-12} \times (50)^2$$
$$= 1.1 \times 10^{-8}\ Jm^{-3}$$

Volume of the cylinder,

$$V = 10\ cm^2 \times 50\ cm = 500\ cm^3 = 5 \times 10^{-4} m^3$$

Energy contained in the cylinder is

$$U = \text{Volume} \times \text{energy density}$$
$$= 5 \times 10^{-4} \times 1.1 \times 10^{-8} = \mathbf{5.5 \times 10^{-12}\ J.}$$

Example 13. *A plane e.m. wave is propagating in the x-direction has a wavelength of 6.0 mm. The electric field is in the y-direction and its maximum magnitude is 33 Vm^{-1}. Write suitable equations for the electric and magnetic fields as a function of x and t.*

Solution. Here $\lambda = 6.0\ mm = 6 \times 10^{-3}$ m,

$$E_0 = 33\ Vm^{-1}$$
$$\omega = 2\pi\nu = \frac{2\pi c}{\lambda} = \frac{2\pi \times 3 \times 10^8}{6 \times 10^{-3}} = \pi \times 10^{11}\ rad\ s^{-1}$$
$$B_0 = \frac{E_0}{c} = \frac{33}{3 \times 10^8} = 1.1 \times 10^{-7} T$$

The equation for the electric field along y-axis can be written as

$$E = E_y = E_0 \sin \omega\left(t - \frac{x}{c}\right)$$
$$= 33 \sin \pi \times 10^{11}\left(t - \frac{x}{c}\right) Vm^{-1}.$$

The equation for the magnetic field along z-axis can be written as

$$B = B_z = B_0 \sin \omega\left(t - \frac{x}{t}\right)$$
$$= 1.1 \times 10^{-7} \sin \pi \times 10^{11}\left(t - \frac{x}{c}\right) \text{tesla.}$$

Example 14. *A laser beam has intensity $2.5 \times 10^{14}\ Wm^{-2}$. Find the amplitudes of electric and magnetic fields in the beam.*

Solution. The intensity of a plane e.m wave,

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

$\therefore$ Amplitude of electric field,

$$E_0 = \sqrt{\frac{2I}{\varepsilon_0 c}} = \sqrt{\frac{2 \times 2.5 \times 10^{14}}{8.85 \times 10^{-12} \times 3 \times 10^8}}$$
$$= \mathbf{4.3 \times 10^8\ Vm^{-1}}$$

Amplitude of magnetic field,

$$B_0 = \frac{E_0}{c} = \frac{4.3 \times 10^8}{3 \times 10^8} = \mathbf{1.44\ T.}$$

Example 15. *A light beam travelling in the x-direction is described by the electric field : $E_y = 270 \sin \omega\left(t - \frac{x}{c}\right)$. An electron is constrained to move along the y-direction with a speed of $2.0 \times 10^7\ ms^{-1}$. Find the maximum electric force and maximum magnetic force on the electron.*

Solution. Maximum electric field,

$$E_0 = 270\ Vm^{-1}$$

Maximum magnetic field,

$$B_0 = \frac{E_0}{c} = \frac{270}{3 \times 10^8} = 9 \times 10^{-7} T,$$

directed along z-direction

Maximum electric force on the electron,

$$F_e = qE_0 = 1.6 \times 10^{-19} \times 270 = \mathbf{4.32 \times 10^{-17}\ N}$$

Maximum electric force on the electron

$$F_m = qvB_0 = 1.6 \times 10^{-19} \times 2.0 \times 10^7 \times 9 \times 10^{-7}$$
$$= \mathbf{2.88 \times 10^{-18}\ N.}$$

Problems For Practice

1. The electric field vector of a plane electromagnetic wave oscillates sinusoidally at a frequency of 4.5×10^{10} Hz. What is the wavelength ? **[CBSE OD 91]**
   (Ans. 6.67×10^{-3} m)
2. The maximum electric field in a plane electromagnetic wave is 600 NC^{-1}. The wave is going in the x-direction and the electric field is in the y-direction. Find the maximum magnetic field in the wave and its direction.
   (Ans. 2×10^{-6}T, z-direction)
3. The frequencies of radio waves in the AM broadcast band range from 0.55×10^6 Hz to 1.6×10^6 Hz. What are the longest and the shortest wavelengths in this band ?
   (Ans. 5.45×10^2 m, 1.87×10^2 m)
4. A radio transmitter operates at a frequency of 880 kHz and a power of 10 kW. Find the number of photons emitted per second. **[CBSE OD 90]**
   (Ans. 1.71×10^{31})
5. The permittivity and permeability of free space are
   $$\varepsilon_0 = 8.85 \times 10^{-12} C^2 N^{-1} m^{-2}$$
   and $\mu_0 = 4\pi \times 10^{-7} TmA^{-1}$, respectively.
   Find the velocity of the electromagnetic wave.
   (Ans. $3 \times 10^8\ ms^{-1}$)
6. In a plane electromagnetic wave of frequency 1.0×10^{12} Hz, the amplitude of the magnetic field is

5.0×10^{-6}T. (*a*) Calculate the amplitude of the electric field. (*b*) What is the total average energy density of the e.m. wave ?

(Ans. 1.5×10^3 Vm^{-1}, 1.0×10^{-5}Jm^{-3})

7. A plane electromagnetic wave is moving along *x*-direction. The frequency of the wave is 10^{15} Hz and the electric field at any point is varying sinusoidally with time with an amplitude of 2 Vm^{-1}. Calculate the average densities of the electric and magnetic fields.

(Ans. 8.85×10^{-12}Jm^{-3}, 8.85×10^{-3}Jm^{-3})

8. The magnetic field in a plane e.m. wave is given by

$$B = (200\,\mu\text{T}) \sin (4.0 \times 10^{-5} \text{s}^{-1}) \left(t - \frac{x}{c}\right)$$

Find the maximum electric field and the average energy density corresponding to the electric field.

(Ans. 6×10^4 Vm^{-1}, 0.008 Jm^{-3})

9. A millimetre wave has a wavelength of 2.00 mm and the oscillating electric field associated with it has an amplitude of 20 Vm^{-1}. Determine the frequency of oscillations of the electric and magnetic fields of this electromagnetic wave. What is the amplitude of the magnetic field oscillations of this wave ? (Ans. 1.5×10^{11} Hz, 6.67×10^{-8} T)

10. In a plane electromagnetic wave, the electric field varies with time having an amplitude 1 Vm^{-1}. The frequency of wave is 0.5×10^{15} Hz. The wave is propagating along *z*-axis. What is the average energy density of (*i*) electric field (*ii*) magnetic field (*iii*) total field, and (*iv*) what is amplitude of magnetic field ?

[Ans. (*i*) 2.21×10^{-12} J m^{-3} (*ii*) 2.21×10^{-12} J m^{-3} (*iii*) 4.42×10^{-12}J m^{-3} (*iv*) 3.33×10^{-9}T]

HINTS

1. $\lambda = \frac{c}{\nu} = \frac{3 \times 10^8}{4.5 \times 10^{10}} = \mathbf{6.67 \times 10^{-3}}$ **m.**

2. $B_0 = \frac{E_0}{c} = \frac{600}{3 \times 10^8} = \mathbf{2 \times 10^{-6}}$ **T**

As the directions of $\vec{E}$, $\vec{B}$ and direction of propagation are mutually perpendicular, so $\vec{B}$ should be along the *z*-direction.

3. Proceed as in Exercise 8.5 on page 8.33.

4. Here $\nu = 880$ kHz $= 880 \times 10^3$ Hz,

$P = 10$ kW $= 10 \times 10^3$ W

Number of photons emitted per second,

$$n = \frac{P}{h\nu} = \frac{10 \times 10^3}{6.6 \times 10^{-34} \times 880 \times 10^3} = \mathbf{1.71 \times 10^{31}}.$$

5. Use $c = \frac{1}{\sqrt{\mu_0 \varepsilon_0}}$

6. (*i*) $E_0 = cB_0 = 3 \times 10^8 \times 5.0 \times 10^{-6} = \mathbf{1.5 \times 10^3}$ **Vm^{-1}.**

(*ii*) $u_{av} = \frac{1}{2} \varepsilon_0 E_0^2 = \frac{1}{2} \times 8.85 \times 10^{-12} \times (1.5 \times 10^3)^2$

$= \mathbf{1.0 \times 10^{-5}}$ **Jm^{-3}.**

7. Proceed as in Example 11 on page 8.14.

8. Here $B_0 = 200\,\mu\text{T} = 2 \times 10^{-4}$T

$E_0 = cB_0 = 3 \times 10^8 \times 2 \times 10^{-4} = \mathbf{6 \times 10^4}$ **V m^{-1}**

$u_E = \frac{1}{4} \varepsilon_0 E_0^2 = \frac{1}{4} \times 8.85 \times 10^{-12} \times (6 \times 10^4)^2$

$= =$ **0.008 Jm^{-3}**

9. Frequency, $\nu = \frac{c}{\lambda} = \frac{3 \times 10^8}{2 \times 10^{-3}} = 1.5 \times 10^{11}$ Hz

$B_0 = \frac{E_0}{c} = \frac{20}{3 \times 10^8} = \mathbf{6.67 \times 10^8}$ **T.**

10. (*i*) $u_E = \frac{1}{4} \varepsilon_0 E_0^2 = \frac{1}{4} \times 8.85 \times 10^{-12} \times 1^2$

$= \mathbf{2.21 \times 10^{-12}}$ **Jm^{-3}**

(*ii*) $u_B = u_E = \mathbf{2.21 \times 10^{-12}}$ **Jm^{-3}**

(*iii*) $u_{av} = u_E + u_B = 2 \times 2.21 \times 10^{-12}$

$= \mathbf{4.42 \times 10^{-12}}$ **J m^{-3}**

(*iv*) $B_0 = \frac{E_0}{c} = \frac{1}{3 \times 10^8} = \mathbf{3.33 \times 10^{-9}}$ **T.**

8.11 ELECTROMAGNETIC SPECTRUM

15. *What is electromagnetic spectrum ? Name the main parts of the electromagnetic spectrum giving their frequency range and source of production. Also give their important properties and uses.*

Electromagnetic spectrum. All the known radiations form a big family of electromagnetic waves which stretch over a large range of wavelengths. *The orderly distribution of the electromagnetic waves in accordance with their wavelength or frequency into distinct groups having widely differing properties is called electromagnetic spectrum.* As shown in Fig. 8.9, the main parts of the e.m. spectrum are γ-rays, X-rays, ultraviolet rays, visible light, infrared rays microwaves and radio waves in the order of increasing wavelength from 10^{-2} Å or 10^{-12} m to 10^6 m.

The various regions of the e.m. spectrum do not have sharply defined boundaries and they overlap. The classification is based roughly on how the waves are produced and/or detected.

We now describe the various regions of the electromagnetic spectrum in the order of increasing frequency.

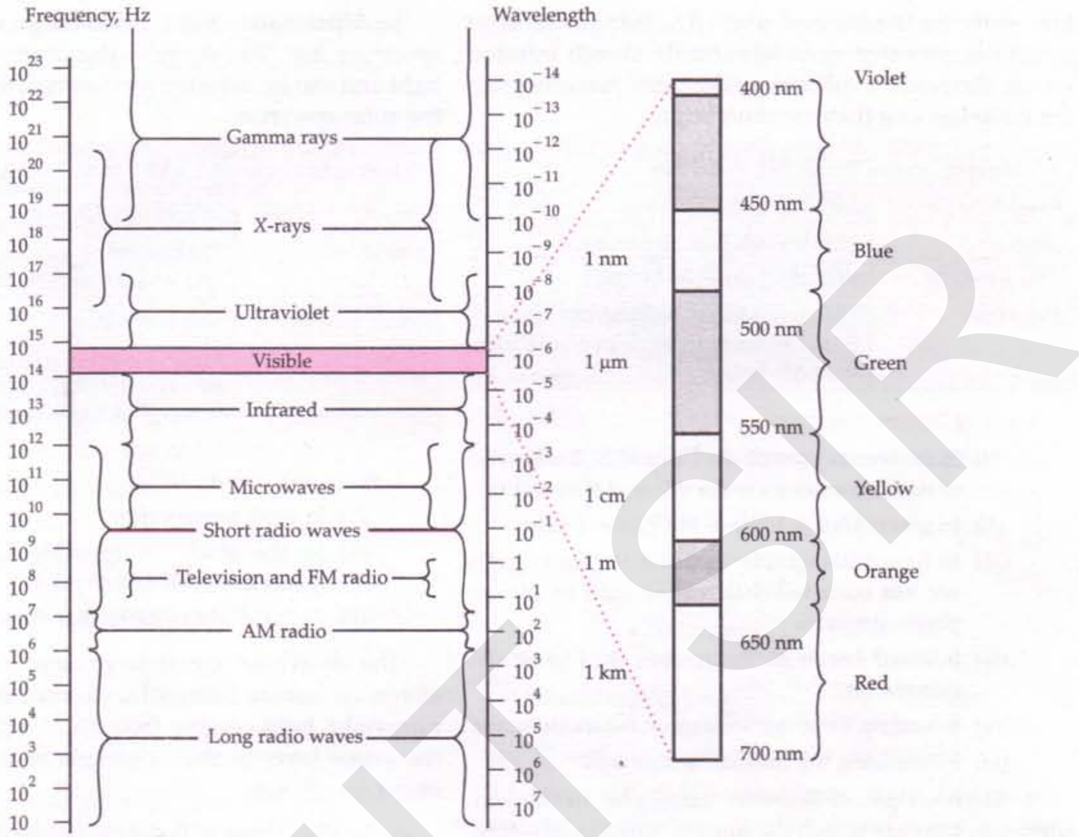

Fig. 8.9 Electromagnetic spectrum.

1. Radio waves. These are the e.m. waves of longest wavelength and minimum frequency.

Wavelength range	600 m to 0.1 m
Frequency range	500 kHz to 1000 MHz
Source	Accelerated motion of charges in conducting wires or oscillating circuits.
Discovered by	Marconi in 1895
Properties	Reflection, diffraction

Uses of radio waves :

(*i*) In radio and television communication systems.

(*ii*) In radioastronomy.

Table 8.1 Some important wireless communication bands

Frequency band	Service
540 – 1600 kHz	Medium wave AM band
3 – 30 MHz	Shortwave AM band
88 – 108 MHz	FM broadcast
54 – 890 MHz	TV Waves
840 – 935 MHz	Cellular Mobile radio

2. Microwaves. They are the e.m. waves having wavelengths next smaller to radiowaves.

Wavelength range	0.3 m to 10^{-3} m
Frequency range	10^9 Hz to 10^{12} Hz
Source	Oscillating currents in special vacuum tubes like klystrons, magnetrons and Gunn diodes.
Discovered by	Marconi in 1895
Properties	Reflection, refraction, diffraction and polarisation. Due to their shorter wavelengths, they can travel as a beam in a signal.

Uses of microwaves :

(*i*) In radar systems for aircraft navigation.

(*ii*) In long-distance communication systems via geostationary satellites.

(*iii*) In microwave ovens.

3. Infrared waves. These radiations lie close to the low-frequency or long-wavelength of the visible spectrum. Infrared waves produce heating effect, so they are also known as ***heat waves*** or ***thermal radiation***.

The water molecules (and also CO_2, NH_3 molecules) present in different materials readily absorb infrared waves, increase the thermal motions and hence heat up the materials and their surroundings.

Wavelength range	5×10^{-3} m to 10^{-6} m
Frequency range	10^{11} Hz to 5×10^{14} Hz
Source	Hot bodies and molecules.
Discovered by	William Herschel in 1800.
Properties	Heating effect, reflection, refraction, diffraction and propagation through fog.

Uses of Infrared waves :

(*i*) In the remote control of a TV or VCR, the keypad of which contains a small infrared transmitter.

(*ii*) In green houses to keep the plants warm.

(*iii*) In haze photography because infrared waves are less scattered than visible light by atmospheric particles.

(*iv*) Infrared lamps in the treatment of muscular complaints.

(*v*) In reading the secret writings on the ancient walls.

(*vi*) In knowing the molecular structure.

4. Visible light. It is a very small part of the e.m. spectrum towards which the human retina is sensitive. The visible light emitted or reflected from bodies around us gives information about the world.

Wavelength range	8×10^{-7} m to 4×10^{-7} m.
Frequency range	4×10^{14} Hz to 7×10^{14} Hz
Source	Radiated by excited atoms in ionised gas and incandescent bodies.
Properties	Reflection, refraction, interference, diffraction, polarisation, photoelectric effect, photographic action, sensation of sight.

Uses of visible light :

(*i*) It provides us the information of the world around us.

(*ii*) It can cause chemical reactions.

The approximate wavelength ranges for lights of different colours are as follows :

Table 8.2 Visible Spectrum

Colour	Wavelength range	Colour	Wavelength range
Violet, indigo	4000 – 4500 Å	Yellow	5700 – 5900 Å
Blue	4500 – 5000 Å	Orange	5900 – 6200 Å
Green	5000 – 5700 Å	Red	6200 – 7500 Å

5. Ultraviolet light. This region of the e.m. spectrum has wavelengths just shorter than visible light and can be detected just beyond the violet end of the solar spectrum.

Wavelength range	3.5×10^{-7} m to 1.5×10^{-7} m
Frequency range	10^{16} Hz to 10^{17} Hz
Source	High voltage gas discharge tubes, arcs of iron and mercury, the sun
Discovered by	Ritter in 1800
Properties	Effect on photographic plate, fluorescence, ionisation, highly energetic, tanning of the human skin.

Uses of ultraviolet light :

(*i*) In food preservation.

(*ii*) In the study of invisible writings, forged documents and finger prints.

(*iii*) In the study of molecular structure.

The ultraviolet light in large quantities has harmful effects on human beings. But fortunately, most of the ultraviolet light coming from the sun is absorbed by the ozone layer in the atomosphere at an altitude of about 40 – 50 km.

6. X-rays. These e.m. waves have wavelengths just shorter than ultraviolet light. As X-rays can pass through many forms of matter, so they have many useful medical and industrial applications.

Wavelength range	100 Å to 0.1 Å
Frequency range	10^{18} Hz to 10^{20} Hz
Source	Sudden deceleration of fast moving electrons by a metal target.
Discovered by	Rontgen in 1895
Properties	Effect on photographic plate, ionisation of gases, photoelectric effect, fluorescence, more energetic than UV rays.

Uses of X-rays :

(*i*) In medical diagnosis because X-rays can pass through flesh but not through bones.

(*ii*) In the study of crystals structure because X-rays can be reflected and diffracted by crystals.

(*iii*) In *engineering* for detecting faults, cracks, flaws and holes in the finished metal products.

(*iv*) In *detective departments* to detect explosives, diamond, gold, etc. in the possession of smugglers.

(*v*) In radiotherapy to cure untracable skin diseases and malignant growths.

7. Gamma rays. These are e.m. radiations of highest frequency range and lowest wavelength range. These are most penerating e.m. waves.

Wavelength range	10^{-14} m to 10^{-10} m.
Frequency range	10^{18} Hz to 10^{22} Hz.
Source	Radioactive nuclei and nuclear reactions. Co - 60 is a pure γ-ray source.
Discovered by	Henry Becqurel in 1896
Properties	Effect on photographic plate, fluorescence, ionisation, diffraction, high penetrating power.

Uses of γ-rays :

(*i*) In radiotherapy for the treatment of malignant tumours.

(*ii*) In the manufacture of polyethylene from ethylene.

(*iii*) To initiate some nuclear reactions.

(*iv*) To preserve food stuffs for a long time because soft γ-rays can kill micro-organisms.

(*v*) To study the structure of atomic nuclei.

Table 8.3 The electromagnetic spectrum

Name	Frequency range (Hz)	Wavelength range	Production	Detection	Main properties and uses
Radiowaves	10^4 to 10^8	> 0.1 m	Rapid acceleration and deaccelerations of electrons in aerials.	Receivers aerials.	Different wavelengths find specialised uses in radio communication.
Microwaves	10^9 to 10^{12}	0.1 m to 1 mm	Klystron valve or magnetron valve.	Point contact diodes.	(*a*) Radar communication. (*b*) Analysis of fine details of molecular and atomic structure. (*c*) Since $\lambda = 3 \times 10^{-2}$ m, useful for demonstration of all wave properties on macroscopic scale.
Infrared	10^{11} to 5×10^{14}	1 mm to 700 nm	Vibration of atoms and molecules.	Thermopiles Bolometer Infrared photographic film.	(*a*) Useful for elucidating molecular structure. (*b*) Less scattered than visible light by atmospheric particles–useful for haze photography.
Visible light	4×10^{14} to 7×10^{14}	700 nm to 400 nm	Electrons in atoms emit light when they move from one energy level to a lower energy level.	Human eye Photocells Photographic film.	(*a*) Detected by stimulating nerve endings of human retina. (*b*) Can cause chemical reaction.
Ultraviolet	10^{16} to 10^{17}	400 nm to 1 nm	Inner shell electrons in atoms moving from one energy level to a lower level.	Photocells Photographic film.	(*a*) Absorbed by glass (*b*) Can cause many chemical reactions, *e.g.*, the tanning of the human skin. (*c*) Ionize atoms in atmosphere, resulting in the ionosphere.
X-rays	10^{16} to 10^{19}	1 nm to 10^{-3} nm	*X*-ray tubes or inner shell electrons.	Photographic film, Geiger tubes, Ionization chamber.	(*a*) Penetrate matter (*e.g.*, radiography) (*b*) Ionize gases (*c*) Cause fluorescence (*d*) Cause photoelectric emission from metals. (*e*) Reflected and diffracted by crystals enabling ionic lattice spacing and N_A (or wavelength) to be measured.
Gamma rays	10^{18} to 10^{22}	< 10^{-3} nm	Radioactive decay of the nucleus.	Photographic film, Geiger tubes, Ionization chamber.	Similar to *X*-rays.

For Your Knowledge

- All electromagnetic waves travel through vacuum with the same speed. They differ basically in their wavelengths or frequencies. As a result, different e.m. waves interact differently with matter.
- The e.m. waves interact with matter through their electric and magnetic fields. These fields set into oscillation the charges present in the matter. The mode of interaction (absorption, scattering, etc.) depends on the wavelength of the e.m. wave and the nature of the atoms and molecules constituting the matter.
- The wavelength of the e.m. wave radiated by any charge system depends on the size of that system. Atomic nuclei radiate γ-rays of wavelengths 10^{-14} to 10^{-15}m. Heavy atoms emit X-rays. Electrons oscillating in a circuit give rise to radiowaves. A transmitting antenna radiates most effectively the radiowaves of wavelength equal to the size of the antenna.
- The infrared waves incident on a substance set into oscillation all its electrons, atoms and molecules. This increases the internal energy and hence the temperature of the substance. That is why infrared waves are also called heat waves.
- Our eyes are most sensitive to the most intense wavelengths of the solar spectrum. That is the centre of sensitivity of our eyes coincides with the centre of the wavelength distribution of the solar radiation.

8.12 EARTH'S ATMOSPHERE

16. *Give classification of earth's atmosphere into different layers.*

Earth's atmosphere. *The thick envelope of air that surrounds the earth is called earth's atmosphere.* It extends to about 400 km above the earth. As we go up, the air pressure decreases gradually. Broadly, the earth's atmosphere can be divided into the following layers or zones.

1. *Troposphere.* This layer extends to a height of 12 km from the earth's surface. Its upper boundary is called ***tropopause***. As height increases, temperature decreases from 290 K to 220 K. This layer contains a large amount of water vapour and clouds are formed in it. It is responsible for all the important wheather phenomena that affect our environment.

2. *Stratosphere.* This layer extends from 12 km to 50 km and its upper boundary is called ***stratopause***. The lower portion of this layer contains a large concentration of ozone, resulting from the dissociation of molecular oxygen by solar ultraviolet radiation in the upper atmosphere. This layer is called ***ozone layer*** or ***ozonosphere*** and extends from 15 km to about 30 km. The temperature of stratosphere rises from 220 K to 280 K.

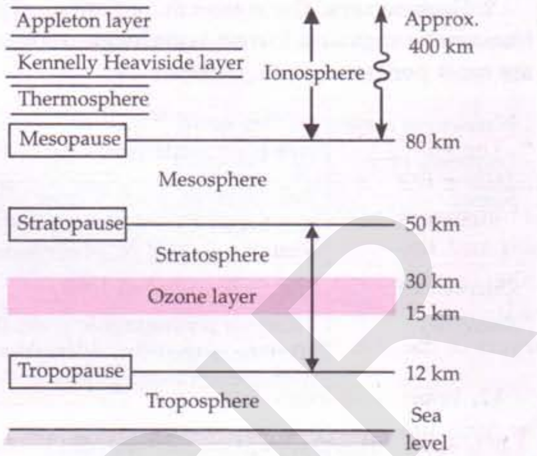

Fig. 8.10 Various layers of earth's atmosphere.

3. *Mesosphere.* This layer extends from 50 km to 80 km. Its upper boundary is called ***mesopause***. The temperature of this region falls from 280 K to 180 K.

4. *Ionosphere.* This layer extends from 80 km to 400 km. Its temperature increases with height from 180 K to 700 K. The ionsophere is mostly composed of electrons and positive ions. This ionisation is caused by ultraviolet radiation and X-rays coming from the sun. The lower portion of the ionosphere extending from 80 km to 95 km is called ***thermosphere***. The concentration of electrons (*i.e.*, electron density) is found to be very large in a region beyond 110 km from the surface of earth which extends vertically for a few kilometres. This layer of electrons is called ***Kennelly Heaviside layer***. Beyond this layer, the electron density decreases considerably until at a height of about 250 km, a layer of electrons is again met. This layer is called ***Appleton layer***.

Except for the ionosphere, the rest of the atmosphere is composed mostly of neutral molecules.

Table 8.4 Salient features of earth's atmosphere

Name of the layer	Extent in km above earth	Fall in density in terms of ground level value	Behaviour of temperature in the layer
Troposphere	0 to 12	From 1 to 10^{-1}	Falls uniformly from 290 K to 220 K
Stratosphere	12 to 50	From 10^{-1} to 10^{-3}	Rises uniformly from 220 K to 280 K
Mesosphere	50 to 80	From 10^{-3} to 10^{-5}	Falls uniformly from 280 K to 180 K
Ionosphere	80 to 300	From 10^{-5} to 10^{-10}	Rises uniformly from 180 K to 700 K

8.13 EFFECT OF EARTH'S ATMOSPHERE ON ELECTROMAGNETIC RADIATION

Introduction

The sun is the main source of the electromagnetic radiation that we receive on the earth. The atmosphere is transparent to the visible radiation as we can see the sun and the stars through it clear ly. However, the other components such as infrared and ultraviolet radiations from the sun are absorbed by different layers of the atmosphere.

17. *What is Greenhouse effect for the atmosphere of the earth and what is its importance ?*

Greenhouse effect. *This is the phenomenon which keeps the earth's surface warm at night.*

The radiation from the sun heats up the earth. Due to its lower temperature, the earth re-radiates it mostly in the infrared region. These infrared radiations cannot pass through the lower atmosphere, they get reflected back by gas molecules. Low lying clouds also reflect them back to the earth. These radiations heat up the objects on the earth's surface and so keep the earth's surface warm at night.

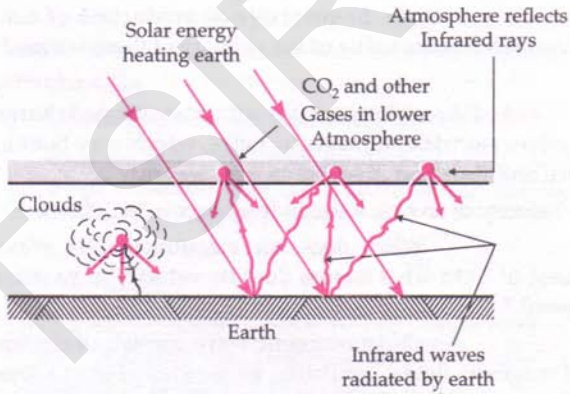

Fig. 8.11 Greenhouse effect.

18. *What is the importance of ozone layer in the atmosphere ?*

Importance of ozone layer. The solar radiation consists of ultraviolet and some other lower wavelength radiations which cause genetic damages to living cells. The ozone layer absorbs these radiations from the sun and prevent them from reaching the earth's surface and causing damage to life. Moreover, it also keeps the earth warm by trapping infrared radiation.

GUIDELINES TO NCERT EXERCISES

8.1. *Figure 8.13 shows a capacitor made of two circular plates each of radius 12 cm and separated by 5.0 mm. The capacitor is being charged by an external source. The charging current is constant and equal to 0.15 A.*

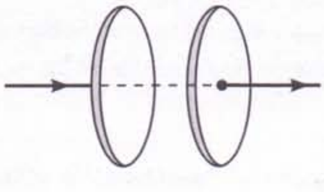

Fig. 8.13

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

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

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

Ans. Radius, $R = 12\text{ cm} = 12 \times 10^{-2}$ m

Plate separation, $d = 5.0\text{ mm} = 5 \times 10^{-3}$ m

Plate area, $A = \pi R^2 = \pi \times (12 \times 10^{-2})^2 \text{m}^2$

(a) Capacitance,

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

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

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

Now the charge at any instant on a capacitor plate is

$$q = CV$$

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

Thus the rate of change of potential difference between the plate is

$$\frac{dV}{dt} = \frac{I}{C}$$

$$= \frac{0.15}{80.1 \times 10^{-12}}$$

$$= \mathbf{1.875 \times 10^9\ Vs^{-1}}$$

(b) From the property of continuity,

Displacement current = Conduction current

$$\therefore \quad I_D = I = \mathbf{0.15\ A}$$

(c) As the sum $(I + I_D)$ is continuous, so the Kirchhoff's first law is valid at capacitor plate if the current in the law is the sum of conduction and displacement currents.

8.2. *A parallel plate capacitor 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 a.c. 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.*

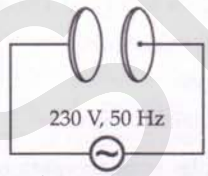

Fig. 8.14

Ans. Here $R = 6.0\text{ cm}$, $C = 100\text{ pF} = 10^{-10}$ F

$V_{rms} = 230$ V , $\omega = 300 \text{ rad s}^{-1}$

(a) Impedance of the capacitor is

$$X_C = \frac{1}{\omega C}$$

$$\therefore \quad I_{rms} = \frac{V_{rms}}{X_C}$$

$$= V_{rms} . \omega C$$

$$= 230 \times 300 \times 10^{-10} \text{ A}$$

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

(b) Yes, the conduction current is equal to the displacement current even if I is oscillating in time.

(c) The formula

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

is valid even if I_D (and hence B) oscillates in time. The formula shows that B and I_D are in phase.

Hence $\quad B_0 = \frac{\mu_0}{2\pi}\frac{r}{R^2} I_0$

where B_0 and I_0 are the amplitudes of the oscillating magnetic field and current, respectively.

Now $\quad I_0 = \sqrt{2}\, I_{rms} = \sqrt{2} \times 6.9\mu \text{ A} = 9.76 \mu \text{ A}$

$$\therefore \quad B_0 = \frac{2 \times 10^{-7} \times 3 \times 10^{-2} \times 9.76 \times 10^{-6}}{(6 \times 10^{-2})^2}$$

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

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

Ans. The wave speed in vacuum is the same for all radiations : $c = 3\times10^{8}\,\text{ms}^{-1}$.

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 ?*

Ans. The electric and magnetic field vectors $\vec{E}$ and $\vec{B}$ of an e.m. wave must be perpendicular to each other and also to the direction of propagation of the wave. Hence vectors $\vec{E}$ and $\vec{B}$ lie in x-y plane in mutually perpendicular directions.

Frequency, $\nu = 30\text{ MHz} = 30\times10^{6}\text{ Hz}$

$\therefore$ Wavelength, $\lambda = \dfrac{c}{\nu} = \dfrac{3\times10^{8}}{30\times10^{6}} = \mathbf{10\ m.}$

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

Ans. Here $\nu_1 = 7.5\text{ MHz} = 7.5\times10^{6}\text{ Hz}$,

$\nu_2 = 12\text{ MHz} = 12\times10^{6}\text{ Hz}$

$$\therefore \quad \lambda_1 = \frac{c}{\nu_1} = \frac{3\times10^{8}}{7.5\times10^{6}} = 40\text{ m}$$

$$\lambda_2 = \frac{c}{\nu_2} = \frac{3\times10^{8}}{12\times10^{6}} = 25\text{ m}$$

Thus the wavelength band is **40 m – 25 m.**

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

Ans. According to Maxwell, a charged particle oscillating with a frequency of 10^{9} Hz, produces electromagnetic waves of the same frequency 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 ?*

Ans. Here $B_0 = 510\text{ nT} = 510\times10^{-9}\text{ T}$

Amplitude of the electric field,

$$E_0 = cB_0 = 3\times10^{8}\times510\times10^{-9} = \mathbf{153\ NC^{-1}}.$$

8.8. *Suppose that the electric field amplitude of an electromagnetic wave is $E_0 = 120\ NC^{-1}$ and that its frequency is $\nu = 50.0$ MHz. (a) Determine, B_0, ω, k and λ. (b) Find expressions for $\vec{E}$ and $\vec{B}$.*

Ans. Here $E_0 = 120\text{ NC}^{-1}$,

$\nu = 50.0\text{ MHz} = 50\times10^{6}\text{ Hz}$

(*a*) $B_0 = \dfrac{E_0}{c} = \dfrac{120\text{ NC}^{-1}}{3\times10^{8}\text{ms}^{-1}} = \mathbf{4\times10^{7}\,T.}$

$$\omega = 2\pi\nu = 2\times3.14\times50\times10^{6} = \mathbf{3.14\times10^{8}\ rad\ s^{-1}}.$$

$$k = \frac{\omega}{c} = \frac{3.14\times10^{8}}{3\times10^{8}} = \mathbf{1.05\ m^{-1}}.$$

$$\lambda = \frac{c}{\nu} = \frac{3\times10^{8}}{50\times10^{6}} = \mathbf{6.00\ m}$$

(*b*) If the wave is propagating along x-axis, then field $\vec{E}$ will be along y-axis and field $\vec{B}$ along z-axis.

$$\therefore \quad \vec{E} = E_0 \sin(kx - \omega t)\,\hat{j}$$

or $\quad \vec{E} = 120\sin(1.05x - 3.14\times10^{8}t)\,\hat{j}\ \text{NC}^{-1}$

where x is in metre and t in second.

$$\vec{B} = B_0 \sin(kx - \omega t)\,\hat{k} = \mathbf{4\times10^{-7}\sin(1.05x - 3.14\times10^{8}t)\,\hat{j}\ tesla.}$$

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 em spectrum. In what way are the different scales of photon energies that you obtain related to the sources of electromagnetic radiation ?*

Ans. Photon energy for $\lambda = 1$ m, is given by

$$E = h\nu = \frac{hc}{\lambda} = \frac{6.63\times10^{-34}\times3\times10^{8}}{1}\text{ J}$$

$$= \frac{6.63\times10^{-34}\times3\times10^{8}}{1.6\times10^{-19}}\text{ eV} = 12.43\times10^{-7}\text{eV}$$

$$= \mathbf{1.24\times10^{-6}\ eV}$$

Photon energy for other wavelengths in the figure for electromagnetic spectrum can be obtained by multiplying appropriate power of ten, as indicated on next page.

Wavelength (in m)	Energy of photon (in eV)
10^{-15} m	1.24×10^{9} eV
10^{-12} m	1.24×10^{6} eV
10^{-9} m	1.24×10^{3} eV
5×10^{-7} m	2.5 eV
10^{-3} m	1.24×10^{-3} eV
10 m	1.24×10^{-7} eV
10^{3} m	1.24×10^{-9} eV

Energy of photon that a source produces indicates the spacings of the relevant energy levels of the source. For example, $\lambda = 10^{-12}$ m corresponds to photon energy $= 1.24 \times 10^{6}$ eV $= 1.24$ MeV. This indicates that nuclear energy levels (transitions between which cause γ-ray emission) are typically spaced by 1 MeV or so. Similarly, a visible wavelength $\lambda = 5 \times 10^{-7}$ m corresponds to photon energy $= 2.5$ eV. This implies that energy levels (transitions between which give visible radiation) are typically spaced by a few eV.

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

(a) What is the wavelength of a wave ?

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

(c) Show that the average energy density of the $\vec{E}$ field equals the average energy density of the $\vec{B}$ field.

[CBSE OD 90]

Ans. (*a*) Wavelength,

$$\lambda = \frac{c}{\nu} = \frac{3 \times 10^{8}}{2.0 \times 10^{10}}$$

$$= \mathbf{1.5 \times 10^{-2}\ m.}$$

(*b*) $B_0 = \frac{E_0}{c} = \frac{48}{3 \times 10^{8}}$

$$= \mathbf{1.6 \times 10^{-7}\ T.}$$

(*c*) Average energy density of $\vec{E}$ field,

$$u_E = \frac{1}{4} \varepsilon_0 E_0^2$$

Average energy density of $\vec{B}$ field,

$$u_B = \frac{1}{4\mu_0} B_0^2$$

But $E_0 = cB_0$ and $c^2 = \frac{1}{\mu_0 \varepsilon_0}$

$\therefore$
$$u_E = \frac{1}{4} \varepsilon_0 E_0^2 = \frac{1}{4} \varepsilon_0 (cB_0)^2$$

$$= \frac{1}{4} \varepsilon_0 \cdot \frac{1}{\mu_0 \varepsilon_0} \cdot B_0^2 = \frac{1}{4\mu_0} B_0^2 = u_B.$$

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

$$\vec{E} = (3.1\ N/C) \cos\ [(1.8\ rad/m)\ y + (5.4 \times 10^{8}\ rad/s)\ t]\ \hat{i}$$

(a) What is the direction of propagation ?

(b) What is the wavelength λ ?

(c) What is the frequency ν ?

(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.

Ans. (*a*) The wave is propagating along negative *y*-direction or its direction is $-\hat{j}$.

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

$$\vec{E} = E_0 \cos \left[2\pi \left(\frac{y}{\lambda} + \nu t \right) \right]$$

we get, $\frac{2\pi}{\lambda} = 1.8$

$\therefore$ Wavelength,

$$\lambda = \frac{2\pi}{1.8} = \frac{2 \times 3.14}{1.8} = \mathbf{3.5\ m.}$$

(*c*) Also, $2\pi\nu = 5.4 \times 10^{6}$

$\therefore$
$$\nu = \frac{5.4 \times 10^{6}}{2\pi} = \frac{5.4 \times 10^{8}}{2 \times 3.14} = 85.9 \times 10^{6}\ \text{Hz}.$$

$$\simeq \mathbf{86\ MHz.}$$

(*d*)
$$B_0 = \frac{E_0}{c} = \frac{3.1\ NC^{-1}}{3 \times 10^{8}\ ms^{-1}}$$

$$= 10.3 \times 10^{-9}\ T = \mathbf{10.3\ nT.}$$

(*e*)
$$\vec{B} = B_0 \cos (ky + \omega t)\ \hat{k}$$

$$= (10.3\ nT) \cos\ [(1.8\ rad/m)\ y + (5.4 \times 10^{8}\ rad/s)\ t]\ \hat{k}.$$

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 1 m from the bulb ?

(b) at a distance of 10 m ?

Ans. The bulb, as a point source, radiates light in all directions. At a distance of *r* m, the surface area of the surrounding sphere,

$$A = 4\pi r^2$$

∴ Average Intensity

$$= \frac{\text{Energy / time}}{\text{Area}} = \frac{\text{Power}}{\text{Area}} = \frac{\text{Power}}{4\pi r^2}$$

(*a*) Average intensity of visible radiation at a distance of 1 m

$$= \frac{5\% \text{ of } 100 \text{ W}}{4\pi (1\text{ m})^2} = \mathbf{0.4 \ Wm^{-2}}.$$

(*b*) Average intensity of visible radiation at a distance of 10 m

$$= \frac{5\% \text{ of } 100 \text{ W}}{4\pi (10\text{ m})^2} = \mathbf{0.004 \ Wm^{-2}}.$$

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

Ans. A body at temperature T produces a continuous spectrum. For a black body, the wavelength corresponding to maximum intensity of radiation is given by Wien's law :

$$\lambda_m T = 0.29 \text{ cmK} = 0.0029 \text{ mK} \qquad \therefore \quad T = \frac{0.0029}{\lambda_m} \text{ K}$$

From the above formula, the temperatures for various wavelengths of the e.m. spectrum will be as follows :

Part of the Spectrum		Wavelength (λ_m in m)	Temperature (T in K)
1.	γ-rays	10^{-12}	29×10^8
2.	X-rays	10^{-10}	29×10^6
3.	Ultraviolet	3×10^{-7}	10^4
4.	Visible	5×10^{-7}	6×10^3
5.	Infrared	3×10^{-5}	10^2
6.	Microwaves	3×10^{-3}	1
7.	Radiowaves	1	29×10^{-4}

These numbers tell us the temperature ranges required to produce e.m. radiations of different wavelengths. To produce visible radiation of $\lambda = 5 \times 10^{-7}$ m, we need to have source at a temperature of 6000 K. A source at lower temperature will also produce this wavelength but not with maximum intensity.

8.14. *Given below are some famous numbers associated with electromagnetic radiation in different contexts in physics. State the part of the e.m. 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 universe).*

(*d*) *5890 Å – 5896 Å (doublet lines of sodium).*

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

Ans. (*a*) *Radiowave* (short wavelength end).

(*b*) *Radiowave* (high frequency or short wavelength end).

(*c*) Here $T = 2.7$ K

By Wien's law,

$$\lambda_m T = 0.29 \text{ cm K}$$

$$\therefore \qquad \lambda_m = \frac{0.29 \text{ cm K}}{2.7 \text{ K}} \simeq 0.11 \text{ cm}$$

This wavelength lies in the *microwave* region of the e.m. spectrum.

(*d*) Yellow part of the *visible region* of the e.m. spectrum.

(*e*) Here $\quad E = 14.4 \text{ keV} = 14.4 \times 10^3 \times 1.6 \times 10^{-19}$ J

As $\quad E = h\nu$

$$\therefore \quad \nu = \frac{E}{h} = \frac{14.4 \times 1.6 \times 10^{-16}}{6.6 \times 10^{-34}} = 3.5 \times 10^{18} \text{ Hz}$$

This frequency lies in the *X-ray* or *soft γ-ray* region of the e.m. spectrum.

8.15. *Answer the following questions :*

(*a*) *Long distance radio broadcasts use short-wave bands. Why ?* **[CBSE D 05]**

(*b*) *It is necessary to use satellites for long distance TV transmission. Why ?* **[CBSE D 05]**

(*c*) *Optical and radiotelescopes are built on the ground but X-ray astronomy is possible only from satellites orbiting the earth. Why ?* **[CBSE OD 09]**

(*d*) *The small ozone layer on top of the stratosphere is crucial for human survival. Why ?* **[CBSE D 14 ; OD 09]**

(*e*) *If the earth did not have an atmosphere, would its average surface temperature be higher or lower than what it is now ?* **[CBSE D 14]**

(*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 ?* **[CBSE OD 95]**

Ans. (*a*) It is because the radiowaves of shortwave band are easily reflected back to the earth by the ionosphere.

(*b*) TV signals being of high frequency are not reflected by the ionosphere. Also, ground wave transmission is possible only upto a limited range. That is why satellites are used for long-distance TV transmission.

(*c*) The earth's atmosphere is transparent to visible light and radiowaves but it absorbs *X*-rays. *X*-ray astronomy is possible only from satellites orbiting the earth. These satellites orbit at a height of 36,000 km, where the atmosphere is very thin and *X*-rays are not absorbed.

(*d*) Ozone layer absorbs ultraviolet radiation from the sun and prevents it from reaching the earth and causing damage to life.

(*e*) The earth radiates infrared waves which are reflected by the gases in the lower atmosphere. This phenomenon, called Green house effect, keeps the earth warm. So if the earth did not have atmosphere, its average temperature would be low due to the absence of Green house effect.

(*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 'nuclear winter'.

Text Based Exercises

TYPE A : VERY SHORT ANSWER QUESTIONS (1 mark each)

1. Name the scientist who first predicted the existence of electromagnetic waves.
2. Name the Indian scientist who first produced the electromagnetic waves.
3. What is displacement current ?
4. Write the SI unit of displacement current.
5. What modification was made by Maxwell in Ampere circuital law ? [Haryana 94]
6. Write an expression for the displacement current.
7. Does the displacement current satisfy the property of continuity ?
8. The charging current for a capacitor is 0.25 A. What is the displacement current across its plates ?
9. Distinguish between conduction current and displacement current.
10. Name the laws associated with the following equations :

    (i) $\oint \vec{E} . d\vec{S} = \frac{q}{\varepsilon_0}$ (ii) $\oint \vec{E} . d\vec{l} = -\frac{d}{dt} \oint \vec{B} . d\vec{S}$

    (iii) $\oint \vec{B} . d\vec{S} = \mu_0 \varepsilon_0 \frac{d}{dt} \oint \vec{E} . d\vec{S}$.
11. Can we apply Maxwell's equations to different types of media, like dielectrics, conductors, plasmas, etc ?
12. Are the Maxwell's equations true for arbitrary high and low values of $\vec{E}$; $\vec{B}$, q, I ?
13. Write down Maxwell's equations for steady electric field. [Haryana 93]
14. Write down Maxwell's equations for steady magnetic field.
15. Which of the four Maxwell's equations shows that electric lines of force cannot form closed loops ?
16. Which of the four Maxwell's equations shows that magnetic lines of force cannot start from a point nor end at a point ?
17. If magnetic monopolies existed, which of the four Maxwell's equations be modified ?
18. A capacitor has been charged by a dc source. What are the magnitudes of conduction and displacement currents, when it is fully charged ? [CBSE D 13]
19. A capacitor is connected to an a.c. source. Is the conduction current in connecting wires equal to the displacement current in the capacitor ?
20. What are electromagnetic waves ?
21. Write an expression for the speed of e.m. waves in free space. [Haryana 98]
22. For an electromagnetic wave, write the relationship between amplitudes of electric and magnetic fields in free space. [CBSE OD 94 ; D 95]
23. State two characteristics of an electromagnetic wave. [CBSE D 98C ; Punjab 02]
24. Can we produce a pure electric or magnetic wave in space ?
25. Is the light emitted by an ordinary electric lamp an electromagnetic wave ?
26. Name the basic source of electromagnetic waves.
27. A plane electromagnetic wave travels in vacuum along x-direction. What can you say about the directions of electric and magnetic field vectors ? [CBSE D 11]

28. What are the directions of electric and magnetic field vectors relative to each other and relative to the direction of propagation of electromagnetic waves ? [CBSE OD 12]
29. What was the range of wavelengths of e.m. waves produced by Professor J.C. Bose ? [CBSE D 93C]
30. What was the range of wavelengths of electromagnetic waves produced by Hertz ?
31. Name the scientist who first set up the transmitter and receiver of electromagnetic waves.
32. What is the significance of the year 1887 in the history of radio communication ?
33. What is electromagnetic spectrum ? [Haryana 97]
34. Name the electromagnetic waves that have frequencies greater than those of ultraviolet light but less than those of gamma rays. [CBSE D 04C]
35. What is approximate wavelength range for visible spectrum ? [Haryana 99C]
36. Write the frequency limit of visible range of electromagnetic spectrum in kHz. [CBSE D 98]
37. Name the electromagnetic radiation which has the largest penetrating power. [CBSE OD 99 ; D 2000]
38. Name the electromagnetic radiation to which the following wavelengths belong :
    (*a*) 10^{-2} m (*b*) 1 Å. [CBSE D 06C]
39. What is approximate wavelength of *X*-rays ? [CBSE OD 90]
40. Name the part of electromagnetic spectrum whose wavelength lies in the range of 10^{-10} m. Give its one use. [CBSE OD 10]
41. Arrange the following in descending order of wavelength : *X*-rays, Radiowaves, Blue light, Infrared light. [CBSE OD 10]
42. Which of the following has the shortest wavelength : microwaves, ultra-violet rays and *X*-rays ? [CBSE OD 10]
43. Arrange the following in the descending order of wavelengths : γ-rays, infrared rays, microwaves, yellow light, radio waves. [CBSE D 13C]
44. Arrange the following e.m. radiations in the increasing order of frequency : *X*-rays, radiowaves, ultra-violet light, blue light, red light and infrared light. [CBSE D 98]
45. What is common between different types of e.m. radiations ?
46. Give the wavelength range and frequency range of γ-rays.
47. What is the order of magnitude of the frequency of vibration of the longest and shortest waves in the electromagnetic spectrum ?
48. Name the electromagnetic radiations used for viewing objects through haze and fog. [CBSE D 97, 04]
49. Name the part of the electromagnetic spectrum which is used in 'green houses' to keep plants warm. [CBSE OD 95C]
50. What is 'greenhouse effect' ? [CBSE F 94 C]
51. Which part of electromagnetic spectrum is absorbed from sunlight by ozone layer ? [CBSE D 10]
52. Name the part of the electromagnetic spectrum suitable for radar systems used in aircraft navigation. [CBSE D 04, 09, 10 ; F 12]
53. What are microwaves ? [Haryana 96]
54. Name the different layers of the earth's atmosphere.
55. Which layer of the earth's atmosphere is useful in long distance radio transmission ?
56. What is the cut-off frequency beyond which the ionosphere does not reflect electromagnetic radiations ? [CBSE OD 94C]
57. What is the range of wavelength of television broadcast. [CBSE F 95]
58. What type of waves are used in telecommunication ?
59. What is the nature of the waves used in radar ? What is their wavelength range ? [CBSE Sample Paper 1997]
60. Name the part of the electromagnetic spectrum of wavelength 10^2 m and mention its one application. **[CBSE D 08]**
61. Name the part of the electromagnetic spectrum of wavelength 10^{-2} m and mention its one application. [CBSE D 08, 09]
62. Identify the part of the electromagnetic spectrum to which the following wavelengths belong :
    (*i*) 1 mm (*ii*) 10^{-11} m. [CBSE OD 08]
63. Identify the part of the electromagnetic spectrum to which the following wavelengths belong :
    (*i*) 10^{-1} m ; (*ii*) 10^{-12} m [CBSE OD 08]
64. From the following, identify the electromagnetic waves having the (*i*) Maximum, (*ii*) Minimum frequency.
    (*i*) Radiowaves (*ii*) Gamma-rays
    (*iii*) Visible light (*iv*) Microwaves
    (*v*) Ultraviolet rays, and (*vi*) Infrared rays. [CBSE Sample Paper 08]
65. Name the characteristic of electromagnetic waves that : (*i*) increases ; (*ii*) remains constant in the electromagnetic spectrum as one moves from radiowave region towards ultraviolet region. [CBSE Sample Paper 08]

66. State which of the two ratios, α and β, defined below, is greater than or less than unity :

$$\alpha = \frac{\nu_{X\text{-ray}}}{\nu_{\text{infrared}}}\;; \quad \beta = \frac{\lambda_{\text{visible}}}{\lambda_{\text{microwaves}}}$$ [CBSE D 07C]

67. The frequency values, ν_1 and ν_2, for two spectral lines of the e.m. spectrum, are found to be 5×10^{20} Hz and 2.5×10^{11} Hz respectively. Find the ratio, λ_1 / λ_2 of their wavelengths. [CBSE OD 07C]

68. The wavelength values, λ_1 and λ_2 of two spectral lines, of the e.m. spectrum, are 1800 nm and 0.12 nm respectively. Calculate the ratio ν_1 / ν_2 of their frequencies. [CBSE OD 07C]

69. The bombardment of a metal target, by high energy electrons, can result in the production of e.m. waves. Name these waves. [CBSE D 08C ; F09]

70. Special devices, like the Klystron valve or the magnetron valve, are used for production of electromagnetic waves. Name these waves and also write one of their applications. [CBSE D 08C ; F09]

71. The frequency of oscillation of the electric field vector of a certain e.m. wave is 5×10^{14} Hz. What is the frequency of oscillation of the corresponding magnetic field vector and to which part of the electromagnetic spectrum does it belong ? [CBSE OD 08]

72. Write the following radiations in ascending order in respect of their frequencies :

X-rays, microwaves, UV rays and radiowaves. [CBSE D 09]

73. Name the EM waves used for studying crystal structure of solids. What is its frequency range ? [CBSE OD 09]

74. Name the electromagnetic waves which (*i*) maintain the earth's warmth and (*ii*) are used in treatment of cancer tumours. [CBSE F 12]

75. To which part of the electromagnetic spectrum does a wave of frequency (*i*) 5×10^{19} Hz (*ii*) 3×10^{13} Hz (*iii*) 5×10^{11} Hz belong ? [CBSE OD 14]

Answers

1. James Clerk Maxwell.

2. J.C. Bose.

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

4. The SI unit of displacement current is ampere (A).

5. A displacement current, $I_D = \varepsilon_0 \dfrac{d\phi_E}{dt}$ was added to the current term of Ampere circuital law to make it logically consistent so that the modified form of Ampere's circuital law is

$$\int \vec{B} . \vec{dl} = \mu_0 (I_C + I_D)$$

6. Displacement current, $I_D = \varepsilon_0 \dfrac{d\phi_E}{dt} = \varepsilon_0 A \dfrac{dE}{dt}$.

7. Yes, the sum of displacement and conduction currents remains constant along a closed path.

8. According to the property of continuity,

Displacement current = Charging current = **0.25 A.**

9. Conduction current is due to the flow of electrons in a circuit. It exists even if electrons flow at a uniform rate. Displacement current is due to time-varying electric field. It does not exist under steady conditions.

10. (*i*) Gauss law of electrostatics.

(*ii*) Faraday's law of electromagnetic induction.

(*iii*) Modified Ampere's law, the term on the right hand side is Maxwell's displacement current.

11. Yes, Maxwell's equations are universally valid.

12. Yes.

13. (*i*) $\oint \vec{E} . \vec{dS} = \dfrac{q}{\varepsilon_0}$ (*ii*) $\oint \vec{E} . \vec{dl} = 0$

14. (*i*) $\oint \vec{B} . \vec{dS} = 0$ (*ii*) $\oint \vec{B} . \vec{dl} = 0$

15. Faraday's law of electromagnetic induction *i.e.*,

$$\int \vec{E} . \vec{dl} = -\frac{d\phi_B}{dt}$$

shows that electric lines of force cannot form closed loops.

16. Gauss's law of magnetostatics *i.e.*, $\int \vec{B} . \vec{dS} = 0$

shows that magnetic lines of force always form closed loops.

17. $\int \vec{B} . \vec{dS} = 0$. This equation is based on the fact that magnetic monopoles do not exist. If they exist, then R.H.S. would contain a term representing pole strength of the monopole, similar to Gauss law in electrostatics.

Also, equation $\int \vec{E} . \vec{dl} = -\dfrac{d\phi_B}{dt}$ would be modified. An additional term I_m representing the current due to flow of magnetic charges would have to be included on R.H.S.

18. When the capacitor gets fully charged,

Conduction current = Displacement current = 0

19. Yes.

20. Electromagnetic waves are the waves radiated by accelerated charges and consist of sinusoidally varying electric and magnetic fields, the oscillations of the two fields are mutually perpendicular to each other as well as to the direction of the propagation of the waves.

21. The speed of an electromagnetic wave in free space is

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

22. The ratio of the amplitudes of electric and magnetic fields equals the speed of light.

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

23. (*a*) The electromagnetic waves travel in free space with a speed of 3×10^8 m / s.

(*b*) They are transverse in nature.

24. No, it is not possible.

25. Yes, it is an e.m. wave.

26. An electric dipole is a basic source of electromagnetic waves.

27. Electric field vectors are along *y*-/*z*- direction and magnetic field vectors are along *z*-/*y*-direction.

28. The directions of electric and magnetic field vectors are perpendicular to each other as well as to the direction of propagation of electromagnetic waves.

29. J.C. Bose was able to produce e.m. waves of the wavelength ranging from 25 mm to 5 mm.

30. Hertz was able to produce e.m. waves of wavelength around 6 m.

31. Hertz.

32. It was in the year 1887 that a German physicist, *Heinrich Hertz*, succeeded for the first time in producing and detecting e.m. waves of wavelength around 6 m.

33. The orderly distribution of electromagnetic radiations of all types according to their wavelength or frequency into distinct groups having widely differing properties is called electromagnetic spectrum.

34. X-rays.

35. The wavelength range for the visible part of the electromagnetic spectrum is 3900 Å to 7600 Å

36. The frequency range for the visible part of the e.m. spectrum is 4×10^{11} kHz to 7.7×10^{11} kHz.

37. γ-rays have the largest penetrating power.

38. (*a*) Microwaves (*b*) X-rays.

39. The approximate wavelength range for X-rays is 0.1 Å – 100 Å.

40. X-rays. These are used in medical diagnosis.

41. In the descending order of wavelength,

Radiowaves > Infrared light > Blue light > X-rays

42. X-rays.

43. In the descending order of wavelength, we have Radiowaves, infrared rays, red light, yellow light, γ-rays.

44. In the increasing order of frequency, we have Radiowaves, infra-red light, red light, blue light, ultra-violet light, X-rays, γ-rays.

45. All e.m. radiations have transverse wave nature and travel with the same speed of 3×10^8 ms^{-1} in free space.

46. Wavelength range of γ-rays is from 0.01 to 1.4 Å and frequency range is from 10^{19} to 10^{24} Hz.

47. Frequency of vibration of longest waves (radiowaves) is of the order of 10^5 Hz. Frequency of vibration of shortest waves (γ-rays) is of the order of 10^{19} to 10^{24} Hz.

48. Infra-red radiations.

49. Infra-red radiation.

50. Greenhouse effect is the phenomenon which keeps the earth's surface warm at night. The earth reflects back infrared part of solar radiation. Infrared rays are reflected back by low lying clouds and lower atmosphere and keep the earth's surface warm at night.

51. Ozone layer absorbs ultraviolet radiation coming from the sun.

52. Microwaves.

53. Microwaves are e.m. waves of wavelength range 10^{-3}m to 0.3 m.

54. Earth's atmosphere can be divided into four layers. These are :

(*i*) Troposphere (*ii*) Stratosphere

(*iii*) Mesosphere (*iv*) Ionosphere.

55. Ionosphere.

56. Ionosphere cannot reflect electromagnetic radiations having frequency higher than 40 MHz.

57. The e.m. waves used in T.V. broadcast have wavelength range from 1.36 m to 3 m.

58. Microwaves.

59. Microwaves. These are electromagnetic waves of the wavelength range 10^{-3}m to 0.3 m.

60. Radiowaves, used in radio and television communication.

61. Microwaves, used in microwave ovens.

62. (*i*) Microwaves, (*ii*) Gamma rays.

63. (*i*) Radiowaves, (*ii*) Gamma rays.

64. (*i*) Gamma-rays have the maximum frequency.
(*ii*) Radiowaves have the minimum frequency.

65. (*i*) The frequency of the electromagnetic waves increases.
(*ii*) The speed of the electromagnetic waves remains constant ($c = 3 \times 10^8 \text{ ms}^{-1}$).

66. $\alpha > 1$ and $\beta < 1$

67. $\frac{\lambda_1}{\lambda_2} = \frac{\nu_2}{\nu_1}$
$= \frac{2.5 \times 10^{11}}{5 \times 10^{20}} = \mathbf{5 \times 10^{-10}}$.

68. $\frac{\nu_1}{\nu_2} = \frac{\lambda_2}{\lambda_1} = \frac{0.12}{1800} = \frac{1}{1500}$.

69. X-rays, used in medical diagnosis.

70. Microwaves, used in microwave ovens.

71. Frequency of oscillation of the magnetic field vector
$$= \mathbf{5 \times 10^{14} \text{ Hz}}$$
This frequency belongs to the *visible region* of the e.m. spectrum.

72. Radiowaves < Microwaves < UV-rays < X-rays.

73. X-rays are used to study crystal structure. Their frequency range is from 10^{16} Hz to 10^{19} Hz.

74. (*i*) Infra-red radiation
(*ii*) Gamma rays.

75. (*i*) X-rays/γ-rays
(*ii*) infra-red radiation
(*iii*) microwaves.

TYPE B : SHORT ANSWER QUESTIONS (2 or 3 marks each)

1. What is displacement current ? Why was this concept introduced ?
2. State and explain Maxwell's modification of Ampere's law. [HPB 1997]
3. Give four characteristics of displacement current.
4. Explain how one 'observes an inconsistency' when Ampere's circuital law is applied to the process of charging a capacitor.
How this 'contradiction' gets removed by introducing the concept of an 'additional current', known as the 'displacement current' ? [CBSE SP 15]
5. Write the generalised expression for the Ampere's circuital law in terms of the conduction current and displacement current. Mention the situation when there is : (*i*) Only conduction current and no displacement current (*ii*) Displacement current and no conduction current. [CBSE F 13]
6. (*a*) A capacitor is connected in series to an ammeter across a d.c. source. Why does the ammeter show a momentary deflection during the charging of the capacitor ? What would be the deflection when it is fully charged ?
(*b*) How is the generalized form of Ampere's critical law obtained to include the term due to displacement current ? [CBSE OD 14C]
7. Conduction and displacement currents are individually discontinuous, but their sum is continuous. Comment. [Haryana 93, 94]
8. State Maxwell equations. [CBSE D 92C]
9. Briefly explain how Maxwell was led to predict the existence of electromagnetic waves.
10. How can we express mathematically a plane electromagnetic wave propagating along X-axis ? Also represent it graphically.
11. (*a*) An e.m. wave is travelling in a medium with a velocity $\vec{v} = v\hat{i}$. Draw a sketch showing the propagation of the e.m. wave, indicating the direction of the oscillating electric and magnetic fields.
(*b*) How are the magnitudes of the electric and magnetic fields related to the velocity of the e.m. wave ? [CBSE D 13]
12. Briefly explain, how does an accelerating charge act as a source of an electromagnetic wave ?
13. Briefly describe the work of Maxwell and Hertz in the field of electromagnetic waves. [CBSE D 97C]
14. What were the contributions of J.C. Bose and Guglielmo Marconi in the field of radio communication ?
15. Give a brief history of the observation of electromagnetic waves. [Punjab 91 ; Haryana 97]
16. Show that electromagnetic waves are transverse in nature. [Haryana 01]
17. Obtain an expression for the energy density of an electromagnetic wave.
18. In an electromagnetic wave, show that the energy density of the *E*-field equals the energy density of the *B*-field.

19. Define intensity of an electromagnetic wave. Obtain an expression for it.
20. Write expressions for (*i*) linear momentum and (*ii*) pressure, exerted by an e.m. wave on a surface.
21. State four basic properties of electromagnetic waves. [CBSE OD 95 ; Punjab 97, 01]
22. Give two characteristics of electromagnetic waves. Write the expression for the velocity of electromagnetic waves in terms of permittivity and magnetic permeability. [CBSE D 93C]
23. What is meant by electromagnetic spectrum ? Give its four uses. [Punjab 99C]
24. Write one property and one use each of infrared rays, ultraviolet rays and radiowaves. [Punjab 02]
25. Draw a sketch of electromagnetic spectrum, showing the relative positions of UV, IR, X-rays and microwaves with respect to visible light. State approximate wavelength of any two. [ICSE 2000]
26. Briefly describe any four regions of the electromagnetic spectrum, mentioning their special properties/features. [ICSE 2002]
27. What are microwaves ? Give their any one use. [Haryana 98]
28. 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. [CBSE OD 08]
29. Identify the following electromagnetic radiations as per the wavelengths given below. Write one application of each.
(*a*) 1 mm (*b*) 10^{-3} nm (*c*) 10^{-8} m [CBSE OD 08]
30. Identify the following electromagnetic radiations as per the frequencies given below. Write one application of each.
(*a*) 10^{20} Hz (*b*) 10^{9} Hz (*c*) 10^{11} Hz. [CBSE OD 08]
31. The following table gives the wavelength range of some constituents of the 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. [CBSE D 08C]
32. Name the electromagnetic radiations having the wavelength range from 1 nm to 10^{-3} nm. Give its two important applications. [CBSE F 09]
33. Name the electromagnetic radiation having the wavelength range from 10^{-1} m to 10^{-3} m. Give its two important applications. [CBSE D 09]
34. Name the electromagnetic radiations having the wavelength range from 1 mm to 700 nm. Give its two important applications. [CBSE F 09]
35. Arrange the following electromagnetic radiations in ascending order of their frequencies :
(*i*) Microwave (*ii*) Radiowave
(*iii*) *X*-rays (*iv*) Gamma rays. [CBSE D 10]
36. Answer the following questions : [CBSE D 14]
(*a*) Name the e.m. waves which are produced during radioactive decay of a nucleus. Write their frequency range.
(*b*) Welders wear special glass goggles while working. Why ? Explain.
(*c*) Why are infrared waves often called as heat waves ? Give their one application.
37. Answer the following :
(*a*) Name the e.m. waves which are used for the treatment of certain forms of cancer. Write their frequency range.
(*b*) Thin ozone layer on top of stratosphere is crucial for human survival. Why ?
(*c*) Why is the amount of the momentum transferred by the e.m. waves incident on the surface so small ? [CBSE D 14]
38. Answer the following questions :
(*a*) Show, by giving a simple example, how e.m. waves carry energy and momentum.
(*b*) How are microwaves produced ? Why is it necessary in microwave ovens to select the frequency of microwaves to match the resonant frequency of water molecules ? [CBSE D 14C]

Answers

1. Refer answers to Q.3 and Q.5 on page 8.38.
2. Refer answer to Q.1 on page 8.1.
3. Refer answer to Q.4 on page 8.3.
4. See property of continuity in Q.1 on page 8.2.

5. Modified Ampere's circuital law is

$$\oint \vec{B}.\vec{dl} = \mu_0\left[I_c + \varepsilon_0 \frac{d\phi_E}{dt}\right]$$

(*i*) In the connecting wires,

$\phi_E = 0$, so $I_d = 0$.

There is only conduction current,

$$I_d = \frac{dq}{dt}.$$

(*ii*) In the region between the capacitor plates,

$I_c = 0$

and $I_d = \varepsilon_0 \frac{d\phi_E}{dt} = \varepsilon_0 \frac{d}{dt}\left(\frac{q}{\varepsilon_0}\right) = \frac{dq}{dt}$.

6. Refer to the solution of Problem 1 on page 8.24.
7. See property of continuity in Q.1 on page 8.2.
8. Refer to point 3 of Glimpses.
9. Refer to solution of Problem 4 on page 8.24.
10. Refer to point 4 of Glimpses, see Fig. 8.5 on page 8.7.
11. (*a*) See Fig. 8.5 on page 8.7. (*b*) $c = \frac{E_0}{B_0}$.
12. Refer answer to Q. 6 on page 8.8.
13. Refer answer to Q. 8 on page 8.10.
14. Refer answer to Q. 8 on page 8.10.
15. Refer answer to Q. 8 on page 8.10.
16. Refer answer to Q. 9 on page 8.10.

17., 18. Refer answer to Q. 10 on page 8.11.

19. Refer answer to Q. 11 on page 8.11.
20. Refer answers to Q. 12 and Q. 13 on page 8.11.
21. Refer to solution of Problem 5 on page 8.24.
22. Refer answer to Q. 14 on page 8.12.
23. Refer answer to Q. 15 on page 8.16.
24. (*i*) Infrared rays produce heating effect. They are useful in haze photography.

(*ii*) Ultraviolet rays cause tanning of human skin. They are used in the study of molecular structure.

(*iii*) These are the e.m. waves of longest wavelength. They are used in radio and TV transmissions.

25. Refer answer to Q. 15 on page 8.16.
26. Refer answer to Q. 15 on page 8.16.
27. Refer answer to Q. 15 on page 8.16.
28. The directions of oscillations of $\vec{E}$ and $\vec{B}$ fields are perpendicular to the direction of propagation of e.m. waves. So these waves are transverse in nature.
29. (*a*) Microwaves, used in radar systems for aircraft navigation.

(*b*) γ-rays, used in the treatment of malignant tumours.

(*c*) Ultraviolet rays, used in food preservation.

30. (*a*) X-rays, in the study of crystal structure.

(*b*) Radiowaves, in radio and television communication systems.

(*c*) Microwaves, in microwave ovens.

31. (*i*) 1 nm to 700 nm, infrared radiations.

(*ii*) $\lambda < 10^{-3}$ nm, Gamma rays.

32. *X*-rays. They are used in

(*i*) medical diagnosis and

(*ii*) in the study of crystal structure.

33. Microwaves. They are used

(*i*) in radar systems and (*ii*) in microwave ovens.

34. Infrared radiations. They are used

(*i*) in remote control devices and

(*ii*) in haze photography.

35. The radiations in ascending order of frequencies are :

Radiowaves < Microwaves < *X*-rays < Gamma rays

36. (*a*) γ-rays. Range : 10^{19} Hz to 10^{23} Hz

(*b*) Welders wear special glass goggles to protect their eyes from large amount of harmful UV radiation produced by welding arc.

(*c*) Infrared waves incident on a substance increase the internal energy and hence the temperature of the substance. That is why they are also called heat waves.

Infrared waves are used in remote control of TV, in green houses, in the treatment of muscular complaints, etc.

37. (*a*) X-rays/γ-rays. Range : 10^{18} Hz to 10^{22} Hz.

(*b*) Ozone layer absorbs ultraviolet radiation from the sun and prevents it from reaching the earth and causing damage to life.

(*c*) If an e.m. wave transfers a total energy *U* to a surface, then total momentum delivered to the surface is

$$p = \frac{U}{c}$$

[For complete absorption of energy *U*]

As the speed of light *c* has a very large value, so the value of momentum transferred is very small.

38. (*a*) Consider a plane perpendicular to the direction of propagation of the wave. An electric charge, on the plane, will be set in

motion by the electric and magnetic fields of em wave, incident on this plane. This illustrates that e.m. waves carry energy and momentum.

(*b*) Microwaves are produced by special vacuum tubes like the Klystron/Magnetron/Gunn diode.

The frequency of microwaves is selected to match the resonant frequency of water molecules, so that energy is transferred efficiently to the kinetic energy of the molecules.

TYPE C : LONG ANSWER QUESTIONS (5 marks each)

1. Describe Hertz's experiment for producing and detecting electromagnetic waves. How did Hertz experimentally establish that (*i*) e.m. waves are transverse in nature, (*ii*) e.m. waves travel with the speed of light, and (*iii*) e.m. waves can be polarised ?
2. Draw a labelled diagram of Hertz's experimental set-up to produce electromagnetic waves. Explain the generation of electromagnetic waves using this set up. Explain how the electromagnetic waves are detected. [CBSE D 06 ; OD 06C]
3. What is electromagnetic spectrum ? Name its main parts, giving the frequency range and source of production in each case. Also give one important use of each part.

Answers

1. Refer answer to Q.7 on page 8.9.
2. Refer answer to Q.7 on page 8.9.
3. Refer answer to Q.15 on page 8.16.

TYPE D : VALUE BASED QUESTIONS (4 marks each)

1. Two friends were passing through the market. They saw two welders using welding machines. One welder was using the goggles and face masks with window in order to protect his face. The other one was welding with naked eyes. They went to the welder who was not using face mask and explained him the advantages of goggles and masks. Next day, the welder bought a set of goggles and began to do his work fearlessly.
   (*a*) What values were displayed by two friends ?
   (*b*) Why do welders wear glass goggles or face masks with glass windows while carrying out welding ?
2. Many people like to watch CID programme on a TV channel. In this programme, a murder mystery is shown. This mystery is solved by a team of CID people. Each member of the team works with full dedication. They collect information and evidences from all possible sources and then tend to lead to correct conclusion. Sometimes they also use ultraviolet rays in the forensic laboratory. Some people get surprised to know the advantage of ultraviolet rays because they are only aware of the fact that ultraviolet rays coming from the sun produce harmful effects.
   (*a*) What values were displayed by the members of CID team ?
   (*b*) What is the use of ultraviolet rays in a forensic laboratory ?
3. Sonam's mother was heating food on a gas stove. Her friend Payal came and saw her mother heating food on the gas stove. Payal told Sonam's mother, "Why don't you buy a microwave oven" ? Sonam's mother replied at once that she doesn't like to use microwave oven. Sonam and Payal convinced her that microwave is not harmful for cooking food. This is an easy, safe and efficient process. Sonam's mother got convinced and immediately ordered for a microwave oven.
   (*a*) What were the values displayed by Sonam and Payal ?
   (*b*) Why does a microwave oven heat up a food item containing water molecules most efficiently ?

Answers

1. (*a*) Knowledge, creating awareness and social responsibility.
   (*b*) Welders wear special glass goggles or face masks with glass windows to protect their eyes from large amount of harmful UV radiation produced by welding arc.
2. (*a*) Team spirit, sense of responsibility and awareness.
   (*b*) UV rays are used in the detection of forged documents, finger prints, etc.
3. (*a*) Caring and creating awareness.
   (*b*) This is because the frequency of the microwaves matches the resonant frequency of water molecules.

Electromagnetic Waves

GLIMPSES

1. Displacement current. It is that current which comes into existence (in addition of conduction current) whenever the electric field and hence the electric flux changes with time. It is equal to ε_0 times the rate of change of electric flux through a given surface.

$$I_D = \varepsilon_0 \frac{d\phi_E}{dt} = \varepsilon_0 A \frac{dE}{dt}$$

2. Modified Ampere circuital law. It states that the line integral of the magnetic field $\vec{B}$ over a closed path is equal to μ_0 times the sum of conduction current I_C and the displacement current (I_D) threading the closed path.

$$\oint \vec{B}.\vec{dl} = \mu_0 (I_C + I_D)$$

$$= \mu_0 \left(I_C + \varepsilon_0 \frac{d\phi_E}{dt} \right)$$

The sum of conduction and displacement currents has an important property of continuity *i.e.*, the sum remains constant along any closed path.

3. Maxwell's equations. These are as follows :

(*i*) *Gauss law of electrostatics* :

$$\oint \vec{E}.\vec{dS} = \frac{q}{\varepsilon_0}$$

(*ii*) *Gauss law of magnetism* :

$$\oint \vec{B}.\vec{dS} = 0$$

(*iii*) *Faraday's law of electromagnetic induction* :

$$\oint \vec{E}.\vec{dl} = -\frac{d\phi_B}{dt} = -\frac{d}{dt}\left[\oint \vec{B}.\vec{dS} \right]$$

(*iv*) Modified Ampere's circuital law :

$$\oint \vec{B}.\vec{dl} = \mu_0 \left[I_C + \varepsilon_0 \frac{d\phi_E}{dt} \right]$$

4. Electromagnetic wave. An electromagnetic wave is a wave radiated by an accelerated charge and which propagates through space as coupled electric and magnetic fields, oscillating perpendicular to each other and to the direction of propagation of the wave.

5. Principle of production of electromagnetic waves. An accelerated charge produces electric and magnetic fields, which vary both in space and time. The two oscillating fields act as sources of each other and hence sustain each other. This results in the propagation of an electromagnetic wave through space.

6. Source of an electromagnetic wave. An accelerating charge produces electromagnetic waves. An electric charge oscillating harmonically with frequency ν, generates electromagnetic waves of the same frequency ν. An electric dipole is a basic source of electromagnetic waves.

An LC-circuit containing inductance L and capacitance C produces electromagnetic waves of frequency,

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

7. Mathematical representation of electromagnetic waves. For a plane electromagnetic wave of frequency ν, wavelength λ, propagating along

x-axis, the electric and magnetic fields may be represented as follows :

$$\vec{E} = E_y\,\hat{j} = E_0 \sin(kx - \omega t)\,\hat{j}$$
$$= E_0 \sin\left[2\pi\left(\frac{x}{\lambda} - \nu t\right)\right]\hat{j}$$
$$= E_0 \sin\left[2\pi\left(\frac{x}{\lambda} - \frac{t}{T}\right)\right]\hat{j}$$
$$E_x = E_z = 0$$

and
$$\vec{B} = B_z\,\hat{k} = B_0 \sin(kx - \omega t)\,\hat{k}$$
$$= B_0 \sin\left[2\pi\left(\frac{x}{\lambda} - \nu t\right)\right]\hat{k}$$
$$= B_0 \sin\left[2\pi\left(\frac{x}{\lambda} - \frac{t}{T}\right)\right]\hat{k}$$
$$B_x = B_y = 0$$

Here E_0 and B_0 are the amplitudes of the electric and magnetic fields respectively.

Propagation constant,
$$k = \frac{2\pi}{\lambda} = \frac{\omega}{c}.$$

8. **Hertz's experiment.** In 1888, Hertz succeeded in experimentally confirming the existence of electromagnetic waves. By using oscillatory LC-circuits, he not only produced and detected electromagnetic waves, but also demonstrated their properties of reflection, refraction, interference and polarisation and established beyond doubt that light radiation has wave nature. He was able to produce e.m. waves of wavelength around 6 m.

9. **Contributions of J.C. Bose and Marconi.** In 1895, Sir J.C. Bose succeeded in producing and observing electromagnetic waves of much shorter wavelength (25 mm to 5 mm).

In 1896, Guglielmo Marconi succeeded in transmitting electromagnetic waves over distances of many kilometres. His experiments marked the beginning of radio communication.

10. **Basic properties of electromagnetic waves.** These are

(*i*) The e.m. waves are produced by accelerated charges and do not require any medium for their propagation.

(*ii*) The oscillations of $\vec{E}$ and $\vec{B}$ fields are perpendicular to each other as well as to the direction of propagation of the wave. So the e.m. waves are transverse in nature.

(*iii*) The oscillations of $\vec{E}$ and $\vec{B}$ fields are in same phase.

(*iv*) All electromagnetic waves travel in free space with same speed c given by

$$c = \frac{1}{\sqrt{\mu_0\,\varepsilon_0}} \simeq 3 \times 10^8\,\text{ms}^{-1}$$

In a material medium of refractive index n, the speed of an electromagnetic wave is given by

$$v = \frac{1}{\sqrt{\mu\varepsilon}} = \frac{c}{\sqrt{\mu_r \varepsilon_r}} = \frac{c}{n}$$

(*v*) The ratio of the amplitudes of electric and magnetic fields is

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

(*vi*) The electromagnetic waves carry energy as they travel through space and this energy is shared equally by the electric and magnetic fields. The average energy of an electromagnetic wave is

$$u = u_E + u_B = \frac{1}{2}\left[\varepsilon_0\,E_0^2 + \frac{B_0^2}{\mu}\right].$$

11. **Momentum of an electromagnetic wave.** If an electromagnetic wave transfers a total energy U to a surface in time t, then total linear momentum delivered to the surface is $p = \dfrac{U}{c}$

12. **Intensity of an electromagnetic wave.** The energy crossing per unit area per unit time in a direction perpendicular to the direction of propagation of the wave is called intensity of the wave.

$$\text{Intensity} = \frac{\text{Energy / time}}{\text{Area}} = \frac{\text{Power}}{\text{Area}}$$

For an e.m. wave of average energy density u,

$$I = uc$$

Also, $$I = \frac{1}{2}\varepsilon_0\,E_0^2\,c = \varepsilon_0\,E_{rms}^2\,c$$

and $$I = \frac{1}{2\mu_0}B_0^2\,c = \frac{1}{\mu_0}B_{rms}^2\,c$$

13. Electromagnetic spectrum. The orderly distribution of the electromagnetic waves in accordance with their wavelength or frequency into distinct groups having widely differing properties is called electromagnetic spectrum. The main parts of an electromagnetic spectrum in the order of increasing wavelength from 10^{-2} Å or 10^{-12} m to 10^{-6} m are γ-rays, X-rays, ultraviolet rays, visible light, infrared rays, microwaves and radiowaves. The different parts of the e.m. spectrum differ in their methods of production and detection.