UNIT-28 : ELECTROMAGNETIC WAVES

Introduction

A changing electric field produces a changing magnetic field and vice versa which gives rise to a transverse wave known as electromagnetic wave. The time-varying electric and magnetic field are mutually perpendicular to each other and also perpendicular to the direction of propagation of this wave (Fig. 1).

The electric vector is responsible for the optical effects of an EM wave and is called the *light vector*.

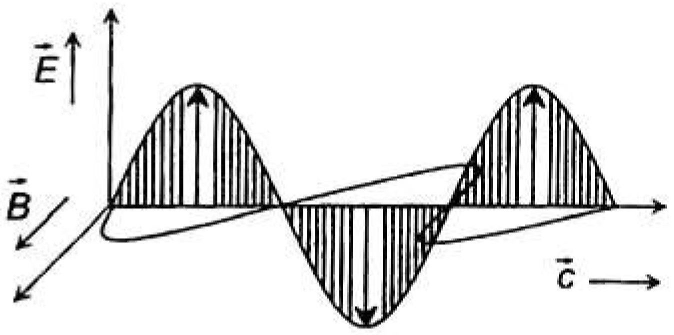


Fig. 1

- $\vec{E}$ and $\vec{B}$ always oscillate in phase.
- $\vec{E}$ and $\vec{B}$ are such that $\vec{E}\times\vec{B}$ is always in the direction of propagation of wave.

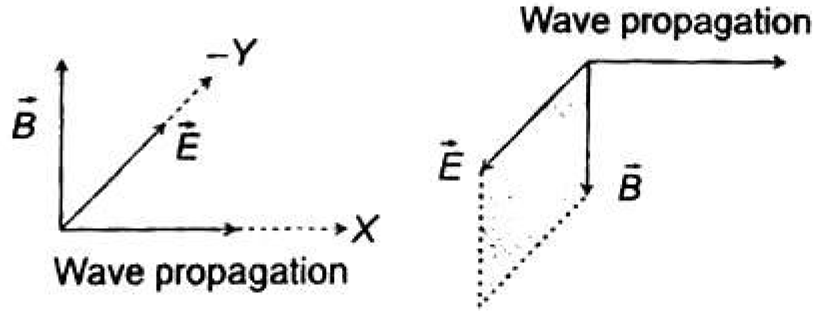


Fig. 2

- The EM wave propagating in the positive x-direction may be represented by

$$E = E_y = E_0 \sin (kx - \omega t)$$

$$B = B_z = B_0 \sin (kx - \omega t)$$

where E (or E_y), B (or B_z) are the instantaneous values of the fields, E_0, B_0 are amplitude of the fields and K = angular wave number $2\pi/\lambda$.

Maxwell's Contribution

Ampere's circuital law According to this law, the line integral of magnetic field along any closed path or circuit is μ_0 times the total current threading the closed circuit, i.e., $\oint \vec{B}.\vec{dl} = \mu_0 i$.

Inconsistency of Ampere's law Maxwell explained that Ampere's law is valid only for steady current or when the electric field does not change with time. To see this inconsistency consider a parallel plate capacitor being charged by a battery. During the charging time varying current flows through connecting wires.

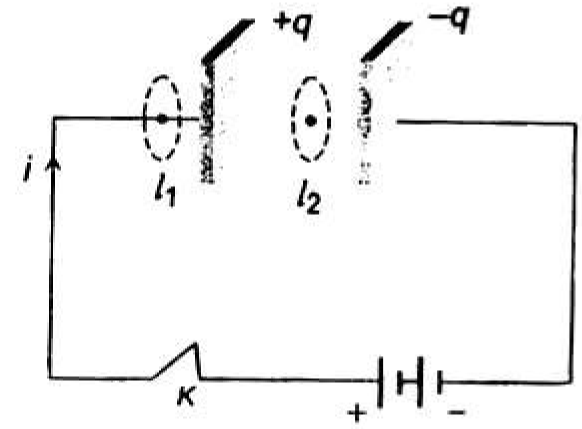


Fig. 3

Applying Ampere's law for loop l_1 and l_2.

$$\oint_{l_1} \vec{B}.\vec{dl} = \mu_0 i$$

But $\oint_{l_2} \vec{B}.\vec{dl} = 0$ (Since no current flows through the region between the plates). But practically it is observed that there is a magnetic field between the plates. Hence, Ampere's law fails

i.e. $\oint_{l_1} \vec{B}.\vec{dl} \neq \mu_0 i$ ·

Modified Ampere's circuital law or Ampere-Maxwell's circuital law Maxwell assumed that some sort of current must be flowing between the capacitor plates during charging process. He named it displacement current. Hence modified law is as follows

$$\oint \vec{B}.\vec{dl} = \mu_0(i_c + i_d)$$

or $$\oint \vec{B}.\vec{dl} = \mu_0\left(i_c + \varepsilon_0 \frac{d\phi_E}{dt}\right)$$

where i_c = conduction current = current due to flow of charges in a conductor and i_d = Displacement current $= \varepsilon_0 \frac{d\phi_E}{dt}$ = current due to the changing electric field between the plates of the capacitor.

Maxwell's equations

- $\oint_s \vec{E}.\vec{ds} = \frac{q}{\varepsilon_0}$ (Gauss's law in electrostatics)
- $\oint_s \vec{B}.\vec{ds} = 0$ (Gauss's law in magnetism)
- $\oint \vec{B}.\vec{dl} = -\frac{d\phi_B}{dt}$ (Faraday's law of EMI)
- $\oint \vec{B}\ \vec{dl} = \mu_o\left(i_c + \varepsilon_o \frac{d\phi_E}{dt}\right)$ (Maxwell-Ampere's circuital law)

Experimental Setup for Producing EM Waves

Hertz experiment based on the fact that a oscillating charge is accelerating continuously, it will radiate electromagnetic waves continuously. In Fig. 4,

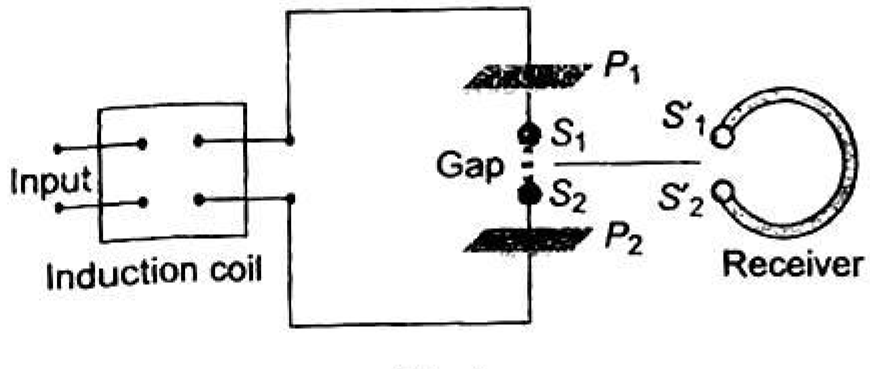


Fig. 4

- The metallic plates (P_1 and P_2) acts as a capacitor.
- The wires connecting spheres S_1 and S_2 to the plates provide a low inductance.
- When a high voltage is applied across metallic plates these plates get discharged by sparking across the narrow gap. The spark will give rise to oscillations which in turn send out electromagnetic waves. Frequency of these wave is given by $\nu = \frac{1}{2\pi\sqrt{LC}}$

The succession of sparks send out a train of such waves which are received by the receiver.

Source, Production, and Nature of EM Waves

- A charge oscillating harmonically is a source of EM waves of same frequency.
- A simple LC oscillator and energy source can produce waves of desired frequency $\left(\nu = \frac{1}{2\pi\sqrt{LC}}\right)$.

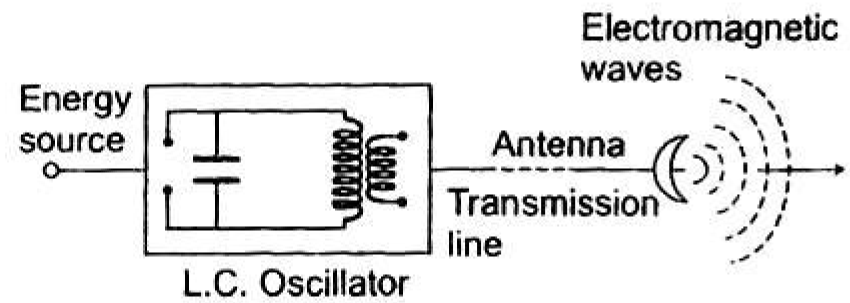


Fig. 5

- The EM waves are transverse in nature. They do not require any material medium for their propagation.

Properties of EM Waves

Speed In free space it's speed

$$c = \frac{1}{\sqrt{\mu_0\varepsilon_0}} = \frac{E_0}{B_0} = 3 \times 10^8 \text{ m/s}.$$

In medium, $\nu = \frac{1}{\sqrt{\mu\varepsilon}}$, where μ_0 = absolute permeability and ε_0 = absolute permittivity.

Energy The energy in an EM waves is divided equally between the electric and magnetic fields.

Energy density of electric field, $u_e = \frac{1}{2}\varepsilon_0 E^2$, energy density of magnetic field, $u_B = \frac{1}{2}\frac{B^2}{\mu_0}$

The total energy per unit volume is $u = u_e + u_m = \frac{1}{2}\varepsilon_0 E^2 + \frac{1}{2}\frac{B^2}{\mu_0}$. Also $u_{av} = \frac{1}{2}\varepsilon_0 E_0^2 = \frac{B_0^2}{2\mu_0}$.

Intensity (I) The energy crossing per unit area per unit time, perpendicular to the direction of propagation of EM wave is called intensity.

i.e., $$I = \frac{\text{Total EM energy}}{\text{Surface area} \times \text{Time}} = \frac{\text{Total energy density} \times \text{Volume}}{\text{Surface area} \times \text{Time}}$$

$$\Rightarrow \quad I = u_{av} \times c = \frac{1}{2}\varepsilon_0 E_0^2 c = \frac{1}{2}\frac{B_0^2}{\mu_0}.c \frac{\text{Watt}}{\text{m}^2}.$$

Momentum EM waves also carries momentum, if a portion of EM wave of energy *u* propagating with speed *c*, then linear momentum $= \frac{\text{Energy } (u)}{\text{Speed } (c)}$.

If wave incident on a completely absorbing surface, then momentum delivered $p = u/c$. If wave incident on a totally reflecting surface, then momentum delivered $-p = 2u/c$.

Poynting vector $(\vec{S})$. In EM waves, the rate of flow of energy crossing a unit area is described by the Poynting vector.

- Its unit is Watt/m^2 and $\vec{S} = \frac{1}{\mu_o}(\vec{E} \times \vec{B}) = c^2 \varepsilon_0 (\vec{E} \times \vec{B})$.
- Because in EM waves $\vec{E}$ and $\vec{B}$ are perpendicular to each other, the magnitude of $\vec{S}$ is

$$|\vec{S}| = \frac{1}{\mu_0} E B \sin 90^\circ = \frac{EB}{\mu_0} = \frac{E^2}{\mu C}.$$

- The direction of $\vec{S}$ does not oscillate but its magnitude varies between zero and a maximum ($S_{max} = E_0 B_0/\mu_0$ each quarter of a period.
- Average value of poynting vector is given by

$$\bar{S} = \frac{1}{2\mu_0} E_0 B_0 = \frac{1}{2}\varepsilon_0 E_0^2 c = \frac{cB_0^2}{2\mu_0}$$

The direction of the poynting vector $\vec{S}$ at any point gives the wave's direction of travel and direction of energy transport the point.

Radiation pressure Is the momentum imparted per second pre unit area. On which the light falls.

For a perfectly reflecting surface, $P_r = 2S/c$; S = poynting vector; c = speed of light.

For a perfectly absorbing surface, $P_a = S/c$.

Wave impedance (Z) The medium offers hindrance to the propagation of wave. Such hindrance is called wave impedance and it is given by $Z = \sqrt{\frac{\mu}{\varepsilon}} = \sqrt{\frac{\mu_r}{\varepsilon_r}}\sqrt{\frac{\mu_0}{\varepsilon_0}}$.

For vacuum or free space, $Z = \sqrt{\frac{\mu_0}{\varepsilon_0}} = 376.6\ \Omega$

EM Spectrum

The whole orderly range of frequencies/wavelengths of the EM waves is known as the EM spectrum.

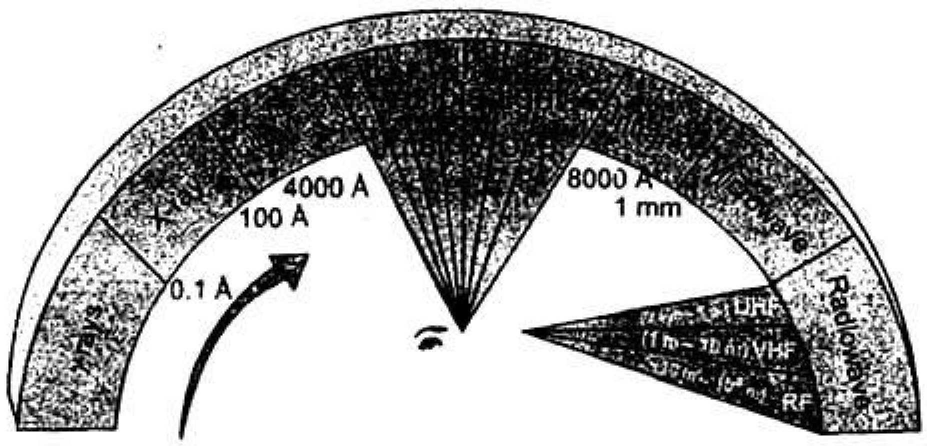


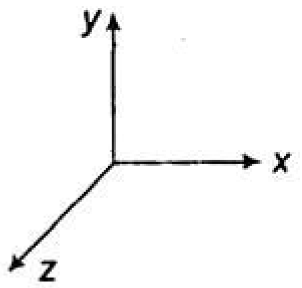
Fig. 6

Table 1 Uses of EM Spectrum

Radiation	Uses
γ-rays	Gives informations on nuclear structure, medical treatment, etc.
X-rays	Medical diagnosis and treatment study of crystal structure, industrial radiograph.
UV- rays	Preserve food, sterilizing the surgical instruments, detecting the invisible writings, finger prints, etc.
Visible light	To see objects.
Infrared rays	To treat, muscular strain for taking photography during the fog, haze, etc.
Micro wave and radio wave	In radar and telecommunication.

EXERCISE

1. If $\vec{E}$ and $\vec{B}$ are the electric and magnetic field vectors of E.M. waves then the direction of propagation of E.M. waves is along the direction of
   (a) $\vec{E}$ (b) $\vec{B}$
   (c) $\vec{E} \times \vec{B}$ (d) None of these
2. Radio waves and visible light in vacuum have
   (a) Same velocity but different wavelength
   (b) Continuous emission spectrum
   (c) Band absorption spectrum
   (d) Line emission spectrum
3. The shortest wavelength of X-rays remitted from an X-ray tube depends upon:
   (a) nature of the gas in the tube
   (b) voltage applied to tube
   (c) current in the tube
   (d) nature of target of the tube.
4. X-rays are not used for radar purposes, because they are not:
   (a) reflected by target
   (b) partly absorbed by target
   (c) electromagnetic waves
   (d) completely absorbed by target.
5. An electromagnetic wave going through vacuum is described by $E = E_0 \sin(kx - \omega t)$. Which of the following is/are independent of the wavelength?
   (a) k (b) ω^2
   (c) k/ω (d) $k\omega^2$.
6. Light wave is travelling along y-direction. If the corresponding $\vec{E}$ vector at any time is along the x-axis, the direction of $\vec{B}$ vector at that time is along



   (a) y-axis (b) x-axis
   (c) + z-axis (d) – z axis
7. What is ozone hole?
   (a) Hole in the ozone layer
   (b) Formation of ozone layer
   (c) Thinning of ozone layer in troposphere
   (d) Reduction in ozone thickness in stratosphere
8. If a source is transmitting electromagnetic wave of frequency 8.2×10^6 Hz, then wavelength of the electromagnetic waves transmitted from the source will be
   (a) 36.6 m (b) 40.5 m
   (c) 42.3 m (d) 50.9 m
9. In an apparatus, the electric field was found to oscillate with an amplitude of 18 V/m. The magnitude of the oscillating magnetic field will be
   (a) $4 \times 10^{-6}\ T$ (b) $6 \times 10^{-8}\ T$
   (c) $9 \times 10^{-9}\ T$ (d) $11 \times 10^{-11}\ T$
10. According to Maxwell's hypothesis, a changing electric field gives rise to
    (a) An e.m.f. (b) Electric current
    (c) Magnetic field (d) Pressure radiant
11. The oscillating electric and magnetic vectors of an electromagnetic wave are oriented along
    (a) The same direction but differ in phase by 90°
    (b) The same direction and are in phase
    (c) Mutually perpendicular directions and are in phase
    (d) Mutually perpendicular directions and differ in phase by 90°
12. An electromagnetic wave travels along z-axis. Which of the following pairs of space and time varying fields would generate such a wave?
    (a) E_x, B_y (b) E_y, B_x
    (c) E_z, B_x (d) E_y, B_z
13. Which of the following rays has the maximum frequency?
    (a) Gamma rays (b) Blue light
    (c) Infrared rays (d) Ultraviolet rays
14. The electromagnetic waves do not transport
    (a) Energy (b) Charge
    (c) Momentum (d) Information
15. An electromagnetic wave going through vacuum is described by $E = E_0 \sin(kx - \omega t)$; $B = B_0 \sin(kx - \omega t)$. Which of the following equations is true?
    (a) $E_0 k = B_0 \omega$ (b) $E_0 \omega = B_0 k$
    (c) $E_0 B_0 = \omega k$ (d) None of these
16. An LC resonant circuit contains a 400 pF capacitor and a 100 μH inductor. It is set into oscillation

coupled to an antenna. The wavelength of the radiated electromagnetic waves is
(a) 377 mm (b) 377 metre
(c) 377 cm (d) 3.77 cm

17. A radio receiver antenna that is 2 m long is oriented along the direction of the electromagnetic wave and receives a signal of intensity 5×10^{-16} W/m^2. The maximum instantaneous potential difference across the two ends of the antenna is
(a) 1.23 μV (b) 1.23 mV
(c) 1.23 V (d) 12.3 mV

18. A TV tower has a height of 100 m. The average population density around the tower is 1000 per km^2. The radius of the earth is 6.4×10^6 m. The population covered by the tower is
(a) 2×10^6 (b) 3×10^6
(c) 4×10^6 (d) 6×10^6

19. Radiations of intensity 0.5 W/m^2 are striking a metal plate. The pressure on the plate is
(a) 0.166×10^{-8} N/m^2 (b) 0.332×10^{-8} N/m^2
(c) 0.111×10^{-8} N/m^2 (d) 0.083×10^{-8} N/m^2

20. Electromagnetic waves travel in a medium which has relative permeability 1.3 and relative permittivity 2.14. Then the speed of the electromagnetic wave in the medium will be
(a) 13.6×10^6 m/s (b) 1.8×10^2 m/s
(c) 3.6×10^8 m/s (d) 1.8×10^8 m/s

21. The intensity of gamma radiation from a given source is I. On passing through 36 mm of lead, it is reduced to $\frac{I}{8}$. The thickness of lead which will reduce the intensity to $\frac{I}{2}$ will be
(a) 18 mm (b) 12 mm
(c) 6 mm (d) 9 mm

22. If c is the speed of electromagnetic waves in vacuum, its speed in a medium of dielectric constant K and relative permeability μ_r is
(a) $v = \frac{1}{\sqrt{\mu_r K}}$ (b) $v = c\sqrt{\mu_r K}$
(c) $v = \frac{c}{\sqrt{\mu_r K}}$ (d) $v = \frac{K}{\sqrt{\mu_r C}}$

23. A parallel plate capacitor of plate separation 2 mm is connected in an electric circuit having source voltage 400 V. if the plate area is 60 cm^2, then the value of displacement current for 10^{-6} sec will be
(a) 1.062 amp (b) 1.062×10^{-2}amp
(c) 1.062×10^{-3} amp (d) 1.062×10^{-4} amp

24. A long straight wire of resistance R, radius a and length l carries a constant current I. The Poynting vector for the wire will be
(a) $\frac{IR}{2\pi al}$ (b) $\frac{IR^2}{al}$
(c) $\frac{I^2R}{al}$ (d) $\frac{I^2R}{2\pi al}$

25. A laser beam can be focussed on an area equal to the square of its wavelength A He-Ne laser radiates energy at the rate of $1mW$ and its wavelength is 632.8 nm. The intensity of focussed beam will be
(a) 1.5×10^{13} W/m^2 (b) 2.5×10^9 W/m^2
(c) 3.5×10^{17} W/m^2 (d) None of these

26. A parallel plate capacitor with plate are A and separation between the plates d, is charged by a constant current i, consider a plane surface of area $A/2$ parallel to the plates and drawn symmetrically between the plates, the displacement current through this area, will be.
(a) i (b) $\frac{i}{2}$
(c) $\frac{i}{4}$ (d) None of these

27. In X-ray tube the accelerating potential applied at the anode is V volt. The minimum wavelength of the emitted X-ray will be:
(a) eV/h (b) h/eV
(c) eV/ch (d) hc/eV.

28. If ϵ_0 and μ_0 represent the permittivity and permeability of vacuum and ϵ and μ represent the permittivity and permeability of medium, the refractive index of the medium is given by:
(a) $\sqrt{\frac{\epsilon_0 \mu_0}{\epsilon \mu}}$ (b) $\sqrt{\frac{\epsilon \mu}{\epsilon_0 \mu_0}}$
(c) $\sqrt{\frac{\epsilon}{\mu_0 \epsilon_0}}$ (d) $\sqrt{\frac{\mu_0 \epsilon_0}{\epsilon}}$

29. The average value of electric energy density in an electromagnetic wave is (E_0 is peak value):
(a) $\frac{1}{2}\varepsilon_0 E_0^2$ (b) $\frac{E_0^2}{2\varepsilon_0}$
(c) $\varepsilon_0 E_0^2$ (d) $\frac{1}{4}\varepsilon_0 E_0^2$

30. The wave impedance of free space is
(a) 0 (b) 376.6 Ω
(c) 1883 Ω (d) 3776 Ω

31. A parallel plate capacitor consists of two circular plates each of radius 12 cm and separated by 5.0 mm. The capacitor is being charged by external source. The charging current is constant and is equal to 0.15 A. The rate of change of potential difference between the plates will be:
(a) 1.873×10^7 V/s (b) 1.873×10^8 V/s
(c) 1.873×10^9 V/s (d) 1.873×10^{10} V/s

32. The sun delivers 10^3 W/m^2 of electromagnetic flux to the earth's surface. The total power that is incident on a roof of dimensions 8 m × 20 m, will be:
(a) 2.56×10^4 W (b) 6.4×10^5 W
(c) 4.0×10^5 W (d) 1.6×10^5 W

33. In previous question, the radiation force on the roof will be:
(a) 8.53×10^{-5} N (b) 2.3×10^{-3} N
(c) 1.33×10^{-3} N (d) 5.33×10^{-4} N

34. A plane electromagnetic wave of wave intensity 6 W/m^2 strikes a small mirror of area 9 cm^2, held perpendicular to the approaching wave. The momentum transferred in kg-ms^{-1} by the wave to the mirror each second will be:
(a) 1.2×10^{-10} (b) 2.4×10^{-9}
(c) 3.6×10^{-8} (d) 4.8×10^{-7}

35. A lamp emits monochromatic green light uniformly in all directions. The lamp is 3% electrical in converting electrical power to electromagnetic waves and consumes 100 W of power. The amplitude of the electric field associated with the electromagnetic radiation at a distance of 5 m from the lamp will be
(a) 1.34 V/m (b) 2.68 V/m
(c) 4.02 V/m (d) 5.36 V/m.

36. Instantaneous displacement current of 1.0 A in the space between the parallel plates of 1 μF capacitor can be established by changing potential difference of:
(a) 10^{-6} V/s (b) 10^6 V/s
(c) 10^{-8} V/s (d) 10^8 V/s.

37. In an apparatus, the electric field was found to oscillate with an amplitude 18 V/m. The amplitude of the oscillating magnetic field will be
(a) 4×10^{-6} T (b) 6×10^{-8} T
(c) 9×10^{-9} T (d) 11×10^{-11} T

38. A point source; of electromagnetic radiation has an average power output of 800 W. The maximum value of electric field at a distance 4.0 m form the source is:
(a) 64.7 V/m (b) 57.8 V/m
(c) 56.72 V/m (d) 54.77 V/m

39. A plane electromagnetic wave
$$F_s = 100 \cos (6 \times 10^8 t + 4x) \text{ V/m}$$
propagates in a medium of dielectric constant. The refractive index is
(a) 1.5 (b) 2.0
(c) 2.4 (d) 4.0

40. The average energy-density of electromagnetic wave given by $E = (50 \text{ N/C}) \sin (\omega t - kx)$ will be nearly:
(a) 10^{-8} J/m^3 (b) 10^{-7} J/m^3
(c) 10^{-6} J/m^3 (d) 10^{-5} J/m^3

41. **Assertion:** The electromagnetic waves of shorter wavelength can travel longer distances on earth's surface than those of longer wavelengths.
Reason: Shorter the wavelength, the larger is the velocity of wave propagation.
Also, shorter the wavelength, shorter is the velocity of wave propagation.

42. **Assertion:** In Hertz experiment, the electric vector of radiation produced by the source gap is parallel to the gap.
Reason: Production of sparks between the detector gap is maximum when it is placed perpendicular to the source gap.

43. **Assertion:** For cooking in a microwave oven, food is always kept in metal containers.
Reason: The energy of microwave is easily transferred to the food in metal container.

44. **Assertion:** *X*-ray astronomy is possible only from satellites orbiting the earth.
Reason: Efficiency of *X*-rays telescope is large as compared to any other telescope.

45. **Assertion:** Ultraviolet radiation are of higher frequency waves are dangerous to human being.
Reason: Ultraviolet radiation are absorbed by the atmosphere

SOLUTIONS

1. (c) E.M. waves travels with perpendicular to E and B which are also perpendicular to each other, $\vec{v} = \vec{E} \times \vec{B}$

2. (a) In vacuum velocity of all EM waves are same but their wavelengths are different.

3. (b) $E = \frac{hc}{\lambda}, E \propto \frac{1}{\lambda}$

or $eV \propto \frac{1}{\lambda}$

4. (a) X-rays are not reflected from target, so cannot be used for radar.

5. (c) $\frac{k}{\omega}$ is independent of λ.

6. (d) Direction of wave propagation is given by $\vec{E} \times \vec{B}$.

7. (d) Ozone hole is depletion of ozone layer in stratosphere because of gases like CFC'S etc.

8. (a) $\lambda = \frac{c}{v} = \frac{3 \times 10^8}{8.2 \times 10^6} = 36.5 \text{ m}$

9. (b) $c = \frac{E}{B} \Rightarrow B = \frac{E}{c} = \frac{18}{3 \times 10^8} = 6 \times 10^{-8} T$

10. (c) According to the Maxwell's EM theory, the EM waves propagation contains electric and magnetic field vibration in mutually perpendicular direction. Thus the changing of electric field give rise to magnetic field.

11. (c) $\vec{E}$ and $\vec{B}$ are mutually perpendicular to each other and are in phase i.e., they become zero and minimum at the same place and at the same time.

12. (a) E_x and B_y would generate a plane EM wave travelling in z-direction. $\vec{E}, \vec{B}$ and $\vec{k}$ form a right handed system $\vec{k}$ is along z-axis. As $\hat{i} \times \hat{j} = \hat{k}$

$\Rightarrow E_x \hat{i} \times B_y \hat{j} = C\hat{k}$ i.e., E is along x-axis and B is along y-axis.

13. (a) $v_{\gamma\text{-rays}} > v_{UV\text{-rays}} > v_{\text{Blue light}} > v_{\text{infrared rays}}$

14. (b) EM waves transport energy, momentum and information but not charge. EM waves are uncharged

15. (a) $\frac{E_0}{B_0} = C$. Also $k = \frac{2\pi}{\lambda}$ and $\omega = 2\pi v$

These relation gives $E_0 K = B_0 \omega$

16. (b) $v = \frac{1}{2\pi\sqrt{LC}}$ and $\lambda = \frac{c}{v}$

17. (a) $I = \frac{1}{2}\varepsilon_0 C E_0^2$

$$\Rightarrow E_0 = \sqrt{\frac{2I}{\varepsilon_0 C}} = \sqrt{\frac{2 \times 5 \times 10^{-16}}{8.85}} = 0.61 \times 10^{-6} \frac{V}{m}$$

Also

$$E_0 = \frac{V_0}{d} \Rightarrow V_0 = E_0 d = 0.61 \times 10^{-6} \times 2 = 1.23\ \mu\text{V}$$

18. (c) Population covered $= 2\pi hR \times$ Population density

$$= 2\pi \times 100 \times 6.4 \times 10^6 \times \frac{1000}{(10^3)^2} = 4 \times 10^6$$

19. (a) Intensity or power per unit area of the radiations

$$P = fv \Rightarrow f = \frac{P}{v} = \frac{0.5}{3 \times 10^8} = 0.166 \times 10^{-8} \text{ N/m}^2$$

20. (d) $v = \frac{c}{\sqrt{\mu_r \varepsilon_r}} = \frac{3 \times 10^8}{\sqrt{1.3 \times 2.14}} = 1.8 \times 10^8 \text{ m/sec}$

21. (b) $I' = Ie^{-\mu x} \Rightarrow x = \frac{1}{\mu}\log_e \frac{I}{I'}$

(where I = original intensity, I' = changed intensity)

$$36 = \frac{1}{\mu}\log_e \frac{I}{I/8} = \frac{3}{\mu}\log_e 2 \qquad \text{...(i)}$$

$$x = \frac{1}{\mu}\log_e \frac{I}{I/2} = \frac{1}{\mu}\log_e 2 \qquad \text{...(ii)}$$

From equation (i) and (ii), $x = 12$ mm.

22. (c) Speed of light in vacuum $c = \frac{1}{\sqrt{\mu_0 \varepsilon_0}}$ and in another medium $v = \frac{1}{\sqrt{\mu\varepsilon}}$

$$\therefore \quad \frac{c}{v} = \sqrt{\frac{\mu\varepsilon}{\mu_0\varepsilon_0}} = \sqrt{\mu_r K} \Rightarrow v = \frac{c}{\sqrt{\mu_r K}}$$

23. (b) $I_D = \varepsilon_0 \frac{d\phi_E}{dt} = \varepsilon_0 \frac{EA}{t} = \varepsilon_0 \left(\frac{V}{d}\right) \cdot \frac{A}{t}$

$$= \frac{8.85 \times 10^{-12} \times 400 \times 60 \times 10^{-4}}{10^{-3} \times 10^{-6}} = 1.602 \times 10^{-2} \text{amp}$$

24. (d) Electric field $E = \frac{V}{l} = \frac{iR}{l}$ (R = Resistance of wire)

Magnetic field at the surface of wire $B = \frac{\mu_0 i}{2\pi a}$ (a = radius of wire)

Hence, Poynting vector, directed radially inward is given by $S = \frac{EB}{\mu_0} = \frac{iR}{\mu_0 l} \cdot \frac{\mu_0 i}{2\pi a} = \frac{i^2 R}{2\pi a l}$

25. (b) Area through which the energy of beam passes $= (6.328 \times 10^{-7}) = 4 \times 10^{-13}\ \text{m}^2$

$$\therefore \quad I = \frac{P}{A} = \frac{10^{-3}}{4 \times 10^{-13}} = 2.5 \times 10^9\ \text{W/m}^2$$

26. (b) Suppose the charge on the capacitor at time t is Q, the electric field between the plates of the capacitor is $E = \frac{Q}{\varepsilon_0 A}$. The flux through the area considered is $\phi_E = \frac{Q}{\varepsilon_0 A} \cdot \frac{A}{2} = \frac{Q}{2\varepsilon_0}$

$\therefore$ The displacement current

$$i_d = \varepsilon_0 \frac{d\phi_E}{dt} = \varepsilon_0 \left(\frac{1}{2\varepsilon_0}\right) \frac{dQ}{dt} = \frac{i}{2}.$$

27. (d) $eV = h\nu = \frac{hc}{\lambda}$

$$\therefore \quad \lambda = \frac{hc}{eV}$$

28. (b) $\mu = \frac{c}{v} = \frac{1}{\sqrt{\mu_0 \epsilon_0}} \times \frac{\sqrt{\mu \epsilon}}{1} = \sqrt{\frac{\mu \epsilon}{\mu_0 \epsilon_0}}$

29. (b) Electric energy density $u_e = \frac{1}{2}\varepsilon_0 \varepsilon_{rms}^2$

$$E_{rms} = \frac{E_0}{\sqrt{2}} \qquad \therefore \quad u_e = \frac{1}{4}\varepsilon_0 E_0^2$$

30. (c) $Z = \sqrt{\frac{\mu_r}{\varepsilon_r}} \times \sqrt{\frac{\mu_0}{\varepsilon_0}}$

$$= \sqrt{\frac{50}{2}} \times 376.6\,\Omega = 1883\,\Omega$$

31. (c) $\frac{dV}{dt} = \frac{1}{C} = \frac{I \cdot d}{A \epsilon_0} = 1.87 \times 10^9$ V/s

32. (d) Power = area × solar constant

$$= 1.62 \times 10^5\ \text{W}$$

33. (d) Force of radiation $= \frac{\text{power}}{c}$

$$= \frac{1.6 \times 10^5}{3 \times 10^8} = 5.32 \times 10^{-4}\text{N}$$

34. (a) Transferred momentum/second to mirror is

$$P = \frac{2AS}{C} = 1.21 \times 10^{-10}\ \text{kg ms}^{-1}$$

35. (b) Mean Intensity $= \frac{P}{4\pi r^2} = \frac{1}{2}\epsilon_0 E^2 \times C$

$$\therefore \quad E = \sqrt{\frac{P}{2\pi r^2 \epsilon_0 C}} = 2.68\ \text{Vm}^{-1}$$

36. (b) $\frac{Q}{E} = \frac{CV}{t}$ or $i_d = C\left(\frac{V}{t}\right)$

or $\frac{V}{t} = \frac{i_d}{C} = \frac{1.0}{10^{-6}} = 10^6$ V/s

37. (b) Here, $E_0 = 18$ V/m, $B_0 = ?$

$$\therefore \quad B_0 = \frac{E_0}{c} = \frac{18}{3 \times 10^8} = 6 \times 10^{-8}\ \text{T}$$

38. (d) Intensity of electromagnetic wave is

$$I = \frac{P_{av}}{2\pi r^2} = \frac{E_0^2}{\mu_0 c}$$

or $E_0 = \sqrt{\frac{\mu_0 C P_{av}}{2\pi r^2}}$

$$= \sqrt{\frac{(4\pi \times 10^{-7}) \times (3 \times 10^8) \times 800}{2\pi \times (4)^2}}$$

$$= 54.77\ \text{V/m}$$

39. (b) Comparing the given equation with equation of plane electromagnetic wave, $E_z = E_0 \cos(\omega t + kx)$, we have $\omega = 6 \times 10^{-8}$ and $k = 4$.

Velocity of light in medium

$$v = \frac{\omega}{K} = \frac{6\times10^8}{4} = \frac{3}{2}\times10^8 \text{ m/s}$$

Refractive index, $\mu = \frac{c}{v} = \frac{3\times10^8}{(3/2)\times10^8} = 2$

40. (a) Average energy density of electromagnetic wave

$$U_{av} = \frac{1}{2}\varepsilon_0 E_0^2 = \frac{1}{2}\times(8.85\times10^{-12})\times(50)^2$$

$$\approx 10^{-8} \text{ J/m}^3$$

41. (c) The electromagnetic waves of shorter wavelength do not suffer much diffraction from the obstacles of earth's atmosphere so they can travel long distance.
Also, shorter the wavelength, shorter is the velocity of wave propagation.

42. (c) Hertz experimentally observed that the production of spark between the detector gap is maximum when it is placed parallel to source gap. This means that the electric vector of radiation produced by the source gap is parallel to the two gaps i.e., in the direction perpendicular to the direction of propagation of the radiation.

43. (d) The atoms of the metallic container are set into forced vibrations by the microwaves. Hence, energy of the microwaves is not efficiently transferred to the metallic container. Hence food in metallic containers cannot be cooked in microwave oven. Normally in microwave oven the energy of waves is transferred to the kinetic energy of the molecules. This raises the temperature of any food.

44. (c) The earth's atmosphere is transparent to visible light and radio waves, but absorbs *X*-rays. Therefore *X*-rays telescope cannot be used on earth surface.

45. (b) The wavelength of these waves ranges between 4000 Å to 100 Å that is smaller wavelength and higher frequency. They are absorbed by atmosphere and convert oxygen into ozone. They cause skin diseases and they are harmful to eye and cause permanent blindness.