XII 6 ELECTROMAGNETIC WAVES

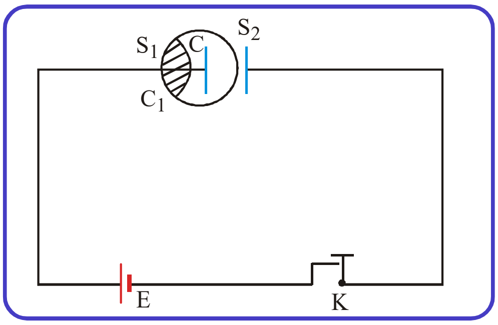
LEARNING OBJECTIVES

1. **Need for Displacement Current.**
2. **Electromagnetic Waves and Their Characteristics (Qualitative Ideas Only).**
3. **Transverse Nature of Electromagnetic Waves.**
4. **Electromagnetic Spectrum (Radio Waves, Microwaves, Infrared, Visible, Ultraviolet, X-Rays, Gamma Rays) Including Elementary Facts About Their Uses.**

KEY CONCEPTS

6.1 DISPLACEMENT CURRENT

* Consider a capacitor C, connected to a cell E and a key K, as shown in Figure. When the key is closed, a momentary current flows through the circuit.



* The current through the connecting wires is due to the directed flow of electrons and is called the conduction current.
* But there is no flow of electrons in the space between the metal plates of the capacitor.
* To make the current continuous through the circuit, Maxwell argued that there is a current flowing through the dielectric region of the capacitor. He called this current as the displacement current.
* This is produced by a time varying electric field.
* The electric field between the capacitor plates is

$E = \frac{\sigma}{\varepsilon_0} = \frac{Q}{\varepsilon_0 A}$, where Q is the charge on the plates and A its surface area

$$\frac{dE}{dt} = \frac{1}{\varepsilon_0 A}\frac{dQ}{dt} = \frac{1}{\varepsilon_0 A} I_D$$

* The displacement current is $\boxed{I_D = \varepsilon_0 A \frac{dE}{dt}}$.
* The current density $J_D = \frac{I_D}{A} = \frac{\varepsilon_0 dE}{dt}$.
* If the medium between the plates is of dielectric constant ε, then $J_D = \varepsilon \frac{dE}{dt} = \frac{dD}{dt}$, where D is the electric displacement.

Maxwell's Correction to Ampere's Law

* According to Ampere's law

$\oint \vec{B}.d\vec{\ell} = \mu_0 I$, i.e., the line integral of magnetic field around a closed loop is equal to μ_0 times the current enclosed by the closed loop.

* For the surface S_1 bound by the closed loop C_1,

$$\oint_{C_1} \vec{B}.d\vec{\ell} = \mu_0 I$$

For the surface S_2 bound by the same closed loop C_1, $\oint_{C_1} \vec{B}.d\vec{\ell} = 0$

because there is no current enclosed by S_2.

* These two results for the same loop C_1 contradict each other. Maxwell solved this problem by adding a term to Ampere's law.
* According to Maxwell, the line integral around a closed loop may be written as

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

where $\varepsilon_0 \frac{d\phi_E}{dt}$, is the displacement current. If E is the electric intensity, the $\phi_E = EA$.

* When this equation is used, we get the correct result for the surfaces S_1 and S_2.

Characteristics of Displacement Current

* Displacement current has nothing to do with current, except that it adds to current density in the Ampere's law. It is called a current because it produces a magnetic field.
* The magnitude of displacement current is equal to the rate of change of electric displacement.
* Unlike conduction current, the displacement current exists when there is a rate of change of electric flux.
* At points where there is an accumulation of charge and hence a discontinuity in conduction current, displacement current helps us to make the total current, continuous across the discontinuity.
* The displacement current is negligible in a good conductor compared to the conduction current at any frequency lower than optical frequencies.
* The addition of displacement current to Ampere's law results in the unification of electric and magnetic phenomena.

6.2 MAXWELL'S EQUATIONS

* Maxwell's equations are equations which describe the fundamental laws of electricity and magnetism.
* These equations help us to conclude that accelerating charges radiate e.m. waves and they travel with the velocity of light in free space.
* The equations, in integral form are,

1. Gauss's Law for Elestrostatics

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

2. Gauss's Law for Magnetism

$\oint \vec{B}.d\vec{A} = 0$. This law tells us that the magnetic flux through any closed surface is zero. This means that magnetic monopoles do not exist.

3. Faraday's Law of Electromagnetic Induction

$\oint \vec{E}.d\vec{\ell} = -\frac{d\phi_B}{dt}$, where $\frac{d\phi_B}{dt}$ is the rate of change of magnetic flux.

The law means that the line integral of electric field is equal to the potential difference (e.m.f.) e.

4. Ampere's Law (with Maxwell Modification)

$$\oint \vec{B}.d\vec{\ell} = \mu_0 \left(I + \varepsilon_0 \frac{d\phi_E}{dt} \right) = \mu_0 (I + I_d)$$

$\frac{d\phi_E}{dt}$ is the rate of change of electric flux. The second term in bracket gives the displacement current.

6.3 ELECTROMAGNETIC WAVES

* When Maxwell's four equations are solved simultaneously, it results into sinusoidal electromagnetic wave equation.

* When any of the fields (magnetic or electric) changes with time, the other field is induced in the space.
* This leads to the generation of electromagnetic disturbance comprising time varying electric and magnetic fields. Such a disturbance can be propagated through space even in the absence of any material medium.
* These disturbances have the properties of a wave and are called electromagnetic waves.
* In the year 1865, Maxwell predicted the electromagnetic waves theoretically. According to him, an accelerated charge sets up a magnetic field in its neighborhood.
* In 1887, Hertz produced and detected electromagnetic waves experimentally at wavelength of about 6 m.
* Seven year later, J.C. Bose became successful in producing electromagnetic waves of wavelength in the range 5 mm to 25mm.
* In 1896, Marconi discovered that if one of the spark gap terminals is connected to an antenna and the other terminal is earthed, the electromagnetic waves radiated could go upto several kilometers.

Production of Electromagnetic Waves

(i) According to Maxwell, an accelerated charge sets up a magnetic field in its neighborhood. The magnetic field, in turn, produces an electric field in that region. Both these field vary with time and act as sources for each other.

(ii) As oscillating charge is accelerated continuously, it will radiate electromagnetic waves continuously.

(iii) In 1888, Hertz demonstrated the production of electromagnetic waves by oscillating charge.

(iv) An induction coil is connected to two spherical electrodes with a narrow gap between them. It acts as a transmitter. The coil provides short voltage surges to the sphere making one positive and the other negative. A spark is generated between the spheres when the voltage between them reaches the breakdown voltage for air. As the air in the gap is ionised, it conducts more rapidly and the discharge between the spheres becomes oscillatory.

(v) The above experimental arrangement is equivalent to an LC circuit, where the inductance is that of the loop and the capacitance is due to the spherical electrodes.

(vi) Electromagnetic waves are radiated at very high frequency ($\approx$ 100 MHz) as a result of oscillation of free charges in the loop.

(vii) Hertz was able to detect these waves using a single loop of wire with its own spark gap (the receiver).

(viii) Sparks were induced across the gap of the receiving electrodes when the frequency of the receiver was adjusted to match that of the transmitter.

6.4 SIMPLE PLANE ELECTROMAGNETIC WAVE

* Electric and magnetic fields in an electromagnetic wave are perpendicular to each other, and to the direction of propagation.
* Figure shows a typical example of a plane electromagnetic wave propagating along the z direction (the fields are shown as a function of the z coordinate, at a given time t).
* The electric field E_x is along the x-axis, and varies sinusoidally with z, at a given time.
* The magnetic field B_y is along the y-axis, and again varies sinusoidally with z.
* The electric and magnetic fields E_x and B_y are perpendicular to each other, and to the direction z of propagation. We can write E_x and B_y as follows:

$$E_x = E_0 \sin(kz - \omega t) \quad ...... (1)$$
$$B_y = B_0 \sin(kz - \omega t) \quad ...... (2)$$

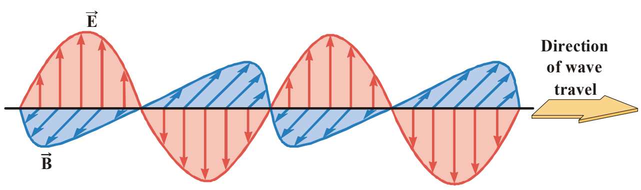


Figure : A linearly polarised electromagnetic wave, propagating in the z-direction with the oscillating electric field E along the x-direction and the oscillating magnetic field B along the y-direction.

* k is related to the wave length λ of the wave by the usual equation $k = \frac{2\pi}{\lambda}$ and ω is the angular frequency. k is the magnitude of the wave vector (or propagation vector) $\hat{k}$ and its direction describes the direction of propagation of the wave.

* The speed of propagation of the wave is (ω/k).

$\omega = ck$, where $c = \frac{1}{\sqrt{\mu_0 \varepsilon_0}}$

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

Properties of Electromagnetic Wave

(i) The electric and magnetic fields satisfy the following wave equations, which can be obtained from Maxwell's third and fourth equations.

$$\frac{\partial^2 E}{\partial x^2} = \mu_0 \varepsilon_0 \frac{\partial^2 E}{\partial f^2}$$

$$\frac{\partial^2 B}{\partial x^2} = \mu_0 \varepsilon_0 \frac{\partial^2 B}{\partial t^2}$$

(ii) Electromagnetic waves travel through vacuum with the speed of light c,

where $c = \frac{1}{\sqrt{\mu_0 \varepsilon_0}} = 3 \times 10^8$ m/s

(iii) The electric and magnetic fields of an electromagnetic wave are perpendicular to each other and also perpendicular to the direction of wave propagation. Hence, these are transverse waves.

(iv) The instantaneous magnitudes of $\vec{E}$ and $\vec{B}$ in an electromagnetic wave are related by the expression $\frac{E}{B} = c$

(v) Electromagnetic waves carry energy. The rate of flow of energy crossing a unit area is described by the **Poynting vector** $\vec{S}$, where $\vec{S} = \frac{1}{\mu_0} \vec{E} \times \vec{B}$

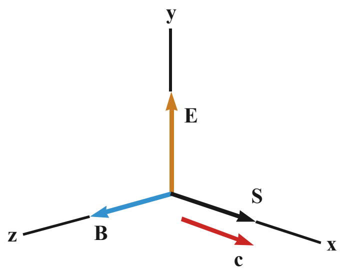


Figure : The Poynting vector S for a plane electromagnetic wave is along the direction of wave propagation.

(vi) Electromagnetic waves carry momentum and hence can exert pressure (P) on surfaces, which is called **radiation pressure**. For an electromagnetic wave with poynting vector $\vec{S}$, incident on a perfectly absorbing surface $P = S/c$ and if incident on a perfectly reflecting surface $P = 2S/c$

(vii) The electric and magnetic field of a sinusoidal plane electromagnetic wave propagating in the positive x-direction can also be written as $E = E_m \sin(kx - \omega t)$; $B = B_m \sin(kx - \omega t)$ where ω is the angular frequency of the wave and k is wave number which are given by

$$\omega = 2\pi f \text{ and } k = \frac{2\pi}{\lambda}$$

(viii) The intensity of a sinusoidal plane electromagnetic wave is defined as the average value of Poynting vector taken over one cycle.

$$S_{av} = \frac{E_m B_m}{2\mu_0} = \frac{E^2{}_m}{2\mu_0 c} = \frac{c}{2\mu_0} B^2{}_m$$

Total energy density: $u = \frac{1}{2}\varepsilon_0 E^2 + \frac{1}{2\mu_0} B^2$

(ix) The fundamental sources of electromagnetic waves are accelerating electric charges. For examples radio waves emitted by an antenna arise from the cotinuous oscillations (and hence acceleration) of charges within the antenna structure.

(x) Electromagnetic waves obey the principle of superposition.

(xi) The electric vector of an electromagnetic field is responsible for all optical effects . For this reason electric vector is also called a light vector

Golden Tips

- The vector product $\vec{E} \times \vec{B}$ always points in the direction of propagation.
- Remember : $\hat{i} \times \hat{j} = \hat{k}$; $\hat{j} \times \hat{k} = \hat{i}$; $\hat{k} \times \hat{i} = \hat{j}$
- The EM wave requires no medium.
- EM waves have the property of polarisation.

EXAMPLE 1

An electromagnetic wave in vacuum has an electric field amplitude of 220 V/m. Calculate the amplitude of the corresponding magnetic field.

SOLUTION:

$$\frac{E}{B} = c \ ; \ \frac{220}{B} = 3.00 \times 10^8$$

so, $B = 7.33 \times 10^{-7}$ T = 733 nT

EXAMPLE 2

Write down expressions for the electric and magnetic fields of a sinusoidal plane electromagnetic wave having a frequency of 3.00GHz and traveling in the positive x direction. The amplitude of the electric field is 300 V/m.

SOLUTION:

$\omega = 2\pi f = 6.00\ \pi \times 10^9\ s^{-1} = 1.88 \times 10^{10}\ s^{-1}$

$$k = \frac{2\pi}{\lambda} = \frac{\omega}{c} = \frac{6.00\pi \times 10^9 s^{-1}}{3.00 \times 10^8 m/s} = 20.0\pi$$

$= 62.8\ m^{-1}$

$$B_{max} = \frac{E}{c} = \frac{300\ V/m}{3.00 \times 10^8 m/s} = 1.00\ \mu T$$

$E = (300\ V/m) \cos(62.8x - 1.88 \times 10^{10} t)$

$B = (1.00\ \mu T) \cos(62.8x - 1.88 \times 10^{10} t)$

EXAMPLE 3

In SI units, the electric field in an electromagnetic wave is $E_y = 100 \sin(1.00 \times 10^7 x - \omega t)$

Find (a) the amplitude of the corresponding magnetic field oscillations, (b) the wavelength λ, and (c) the frequency f.

SOLUTION:

(a) $$B_{max} = \frac{E}{c} = \frac{100\ V/m}{3.00 \times 10^8 m/s}$$

$= 3.33 \times 10^{-7}\ T = 0.333\ \mu T$

(b) $$\lambda = \frac{2\pi}{k} = \frac{2\pi}{1.00 \times 10^7 m^{-1}} = 0.628\ \mu m$$

(c) $$f = \frac{c}{\lambda} = \frac{3.00 \times 10^8 m/s}{6.28 \times 10^{-7} m} = 4.77 \times 10^{14}\ Hz$$

EXAMPLE 4

At one location on the Earth, the rms value of the magnetic field caused by solar radiation is 1.80 μT. From this value calculate (a) the rms electric field due to solar radiation, (b) the average energy density of the solar component of electromagnetic radiation at this location, and (c) the average magnitude of the Poynting vector for the Sun's radiation.

SOLUTION:

(a) $E = cB = (3.00 \times 10^8\ m/s)(1.80 \times 10^{-6}\ T)$

$= 540\ V/m$

(b) $$u_{av} = \frac{B^2}{\mu_0} = \frac{(180 \times 10^{-6})^2}{4\pi \times 10^{-7}} = 2.58\ \mu J/m^3$$

(c) $S_{av} = cu_{av} = (3.00 \times 10^8)(2.58 \times 10^{-6})$

$= 773\ W/m^2$

EXAMPLE 5

A 100-mW laser beam is reflected back upon itself by a mirror. Calculate the force on the mirror.

SOLUTION:

The pressure P upon the mirror is, $P = \frac{2S_{av}}{c}$

where A is the cross-sectional area of the beam

and $S_{av} = \frac{P}{A}$

The force on the mirror is then

$$F = PA = \frac{2}{c}\left(\frac{P}{A}\right)A = \frac{2P}{c}$$

$$F = \frac{2(100 \times 10^{-3})}{3 \times 10^8} = 6.67 \times 10^{-10}\ N$$

Checkup 1

Q.1 When light (or other electromagnetic radiation) travels across a given region, what is it that oscillates? What is it that is transported?

Q.2 Do all current-carrying conductors emit electromagnetic waves? Explain.

Q.3 What is the fundamental source of electromagnetic radiation?

Q.4 If a high-frequency current is passed through a solenoid containing a metallic core, the core becomes warm due to induction. Explain why the material rises in temperature in this situation.

Q.5 If you charge a comb by running it through your hair and then hold the comb next to a bar magnet, do the electric and magnetic fields produced constitute an electromagnetic wave?

Q.6 How much electromagnetic energy per cubic meter is contained in sunlight, if the intensity of sunlight at the Earth's surface under a fairly clear sky is 1000 W/m^2?

Q.7 What is the average magnitude of the Poynting vector 5.00 miles from a radio transmitter broadcasting isotropically with an average power of 250 kW?

Q.8 A monochromatic light source emits 100 W of electromagnetic power uniformly in all directions. (a) Calculate the average electric-field energy density 1.00 m from the source. (b) Calculate the average magnetic-field energy density at the same distance from the source. (c) Find the wave intensity at this location.

Q.9 A radio wave transmits 25.0 W/m^2 of power per unit area. A flat surface of area A is perpendicular to the direction of propagation of the wave. Calculate the radiation pressure on it, assuming the surface is a perfect absorber.

6.5 ELECTROMAGNETIC SPECTRUM

* EM waves can exist at every frequency, without restriction. The properties of EM waves and their interactions with matter depend on the frequency of the wave.
* The electromagnetic spectrum-the range of frequencies (and wavelengths)-is traditionally divided into six or seven named regions.

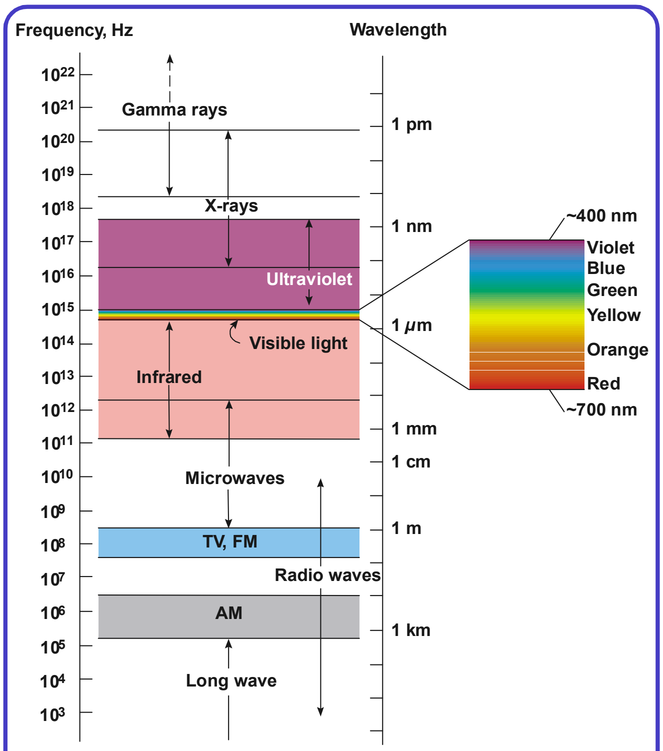


Figure : The Electromagnetic Spectrum

* **Visible light :** Visible light is the part of the spectrum that can be detected by the human eye. This seems like a pretty cut and-dried definition, but actually the sensitivity of the eye falls off gradually at both ends of the visible spectrum. Just as the range of frequencies of sound that can be heard varies from person to person, so does the range of frequencies of light that can be seen. For an average range we take frequencies of 430 THz (I THz = 10^{12} Hz) to 750 THz, corresponding to wavelengths in vacuum of 700-400 nm. Light containing a mixture of all the wavelengths in the visible range appears white.

White light can be separated by a prism into the colors red (700-620 nm), orange (620-600 nm), yellow (600-580 nm), green (580-490 nm), blue (490-450 nm), and violet (450-400 nm). Red has the lowest frequency (longest wavelength) and violet has the highest frequency (shortest wavelength).

It is not a coincidence that the human eye evolved to be most sensitive to the range of EM waves that are most intense in sunlight. However, other animals have visible ranges that differ from that of humans; the range is often well suited to the particular needs of the animal.

* **Infrared :** After visible light, the first parts of the EM spectrum to be discovered were those on either side of the visible: infrared and ultraviolet (discovered in 1800 and 1801, respectively). The prefix infra- means below; infrared radiation (IR) is lower in frequency than visible light. IR extends from the low frequency (red) edge of the visible to a frequency of about 300 GHz (λ = 1mm). The astronomer Willial Herschel (1738-1822) discovered IR in 1800 while studying the temperature rise caused by the light emerging from a prism.

  The thermal radiation given off by objects near room temperature is primarily infrared, with the peak of the radiated IR at a wavelength of about 0.01 mm = 10μm.

* **Ultraviolet :** The prefix ultra- means above; ultraviolet (UV) radiation is higher in frequency than visible light. UV ranges in wavelength from the shortest visible wavelength (about 380 nm) down to about 10 nm. There is plenty of UV in the Sun's radiation; its effects on human skin include tanning, sunburn, formation of vitamin D, and melanoma.

* **Radio Waves :** After IR and UV were identified, most of the nineteenth century passed before any of the outlying regions of the EM spectrum were discovered. The lowest frequencies (up to about I GHz) and longest wavelengths (down to about 0.3 m) are called radio waves. Radio waves were discovered in 1888 by Heinrich Hertz. AM and FM radio, VHF and UHF TV broadcasts, occupy assigned frequency bands within the radio wave part of the spectrum.

* **Microwaves :** Microwaves are the part of the EM spectrum lying between radio waves and IR, with vacuum wavelengths roughly from 1 mm to 30 cm. Microwaves are used in communications (cell phones and satellite TV) and in radar.

  A microwave oven immerse food in microwaves with a lying in vacuum of about 12 cm. Water is a good absorber of microwaves because the water molecule is polar.

* **X- Rays and Gamma Rays :** Higher in frequency and shorter in wavelength than UV are x-rays and gamma rays, which were discovered in 1895 and 1900, respectively.

  The two names are still used, based on the source of the waves, mostly for historical reasons. There is considerable overlap in the frequencies of the EM waves generated by these two methods, so today the distinction is somewhat arbitrary.

  X-rays were unexpectedly discovered by Wilhelm Konrad Rontgen (1845-1923) when he accelerated electrons to high energies and smashed them into a target. The large deceleration of the electrons as they come to rest in the target produces the x-rays.

  Most diagnostic x-rays used in medicine and dentistry have wavelengths between 10 and 60 pm. (1 pm = 10^{-12} m)

  Gamma rays were first observed in the decay of radioactive nuclei on Earth. Pulsars, neutron stars, black holes, and explosions of supernovae are sources of gamma rays that travel earth, but fortunately for us-gamma rays are absorbed by the atmosphere. Only when detectors were placed high in the atmosphere and above it by using balloons and satellites did the science of gamma-rays astronomy develop.

* **Different Types of Electromagnetic Waves**

Type	Wavelength	Production	Detection
Radio	> 0.1 m	Rapid acceleration and decelerations of electrons in aerials	Receiver's aerials
Microwave	0.1m to 1 mm	Klystron valve or magnetron valve	Point contact diodes
Infra-red	1mm to 700 nm	Vibration of atoms and molecules	Thermopiles Bolometer, Infrared photographic film
Light	700 nm to 400 nm	Electrons in atoms emit light when they move from one energy level to a lower energy level	The eye Photocells Photographic film
Ultraviolet	400 nm to 1nm	Inner shell electrons in atoms moving from one energy level to a lower level	Photocells Photographic film
X-rays	1nm to 10^{-3} nm	X-ray tubes or inner shell electrons	Photographic film Geiger tubes Ionisation chamber
Gamma rays	$<10^{-3}$ nm	Radioactive decay of the nucleus	Photographic film Geiger tubes Ionisation chamber

EXAMPLE 6

The human eye is most sensitive to light having a wavelength of 5.50×10^{-7} m, which is in the green-yellow region of the visible electromagnetic spectrum. What is the frequency of this light?

SOLUTION:

$$f = \frac{c}{\lambda} = \frac{3.00 \times 10^8 \text{ m/s}}{5.50 \times 10^{-7} \text{ m}} = 5.45 \times 10^{14} \text{ Hz}$$

IMPORTANT POINTS

* Displacement current

$$I_d = \varepsilon_0 \frac{d}{dt}\phi_E = \varepsilon_0 \frac{d\oint \vec{E}\cdot d\vec{s}}{dt} = \frac{CdV}{dt}$$

* Maxwell's equations

(a) $\oint \vec{E}\cdot d\vec{s} = \frac{q}{\varepsilon_0}$

(b) $\oint \vec{B}\cdot d\vec{s} = 0$

(c) $\oint \vec{E}\cdot d\vec{\ell} = -\frac{d}{dt}\phi_B = \frac{-d}{dt}\oint \vec{B}\cdot d\vec{s}$

(d) $\oint \vec{B}\cdot d\vec{\ell} = \mu_0\left(1 + \varepsilon_0 \frac{d\phi_E}{dt}\right)$

* $E_y = E_0 \sin(\omega t - kx)$ and $B_z = E_0 \sin(\omega t - kx)$

$$c_{vacuum} = \frac{1}{\sqrt{\mu_0 \varepsilon_0}}, \; c_{medium} = \frac{1}{\sqrt{\mu_r \mu_0 \varepsilon_r \varepsilon_0}}$$

* $\frac{E_0}{B_0} = \frac{E_{rms}}{B_{rms}} = \frac{E}{B} = c$

* Poynting vector, $\vec{S} = \frac{\vec{E} \times \vec{B}}{\mu_0}$

= Intensity (I) of wave

* Average intensity of wave

I_{av} = Average energy density × (Speed of light)

or $I_{av} = U_{av} \cdot c = \frac{E_0 B_0}{2\mu_0} = \frac{E_0^2}{2c\mu_0} = \frac{cB_0^2}{2\mu_0}$

* Instantaneous energy density

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

* Average energy density

$$u_{av} = \frac{1}{4}\varepsilon_0 E_0^2 + \frac{B_0^2}{4\mu_0} = \frac{\varepsilon_0 E_0^2}{2} = \frac{B_0^2}{2\mu_0}$$

* Energy = (momentum) . c or U = pc

* Radiation pressure

$= \frac{\text{Intensity}}{c}$ (when the wave is totally absorbed)

$= \frac{2\,(\text{Intensity})}{c}$ (when the wave is totally reflected)

* Intensity of wave from a source at a distance r from it is proportional to

$\frac{1}{r^2}$ (For a point source)

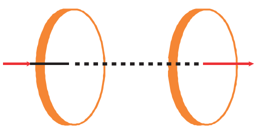
$\frac{1}{r}$ (For a line source)

For a plane source intensity is independent of r.

SOLVED EXAMPLES

EXAMPLE 1

Figure 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 (not shown in the figure). The charging current is constant and equal to 0.15A.



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

(b) Obtain the displacement current across the plates.

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

SOLUTION:

(a) Using $C = \frac{\varepsilon_0 A}{d}$ we get

$$C = \frac{8.854\times10^{-12}\times\pi r^2}{d}$$

$$= \frac{8.854\times10^{-12}\times3.14\times(12\times10^{-2})^2}{5\times10^{-3}}$$

$= 80.1$ pF

$V = \frac{Q}{C}$. we get $\frac{dV}{dt} = \frac{1}{C}\frac{dQ}{dt}$

or $\frac{dV}{dt} = \frac{I}{C} = \frac{0.15}{80.1\times10^{-12}}$

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

(b) Displacement current,

$$I_d = \varepsilon_0\frac{d\phi_E}{dt} = \varepsilon_0\frac{d\,(EA)}{dt} = \varepsilon_0 A\frac{dE}{dt}$$

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

(Across capacitor $\phi_E = EA$, ignoring end correction)

$= (8 \times 10^{-12})\,(1.875 \times 10^{10}) = 0.15$ A

Displacement current = Conduction current

(c) Yes. Kirchhoff's first rule is valid at each plate of the capacitor provided that we take the sum of conduction and displacement currents.

EXAMPLE 2

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

SOLUTION:

$\nu = \frac{c}{\lambda}$; $\lambda = \frac{c}{\nu}$ i.e., $\lambda = \frac{3\times10^8}{7.5\times10^6} = 40$m

$\lambda' = \frac{3\times10^8}{12\times10^6} = 25$m

Corresponding wavelength band is 40m to 25m.

EXAMPLE 3

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?

SOLUTION:

Using $\frac{E_0}{B_0} = c$, we get $E_0 = B_0 c$

i.e., $E = (510 \times 10^{-9})\,(3 \times 10^8) = 153\ NC^{-1}$.

EXAMPLE 4

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

$$\vec{E} = \{(3.1 \text{ N/C}) \cos[(1.8 \text{ rad/m})\, y + (5.4 \times 10^6 \text{ rad/s})\, t]\}\, \hat{i}.$$

(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.

SOLUTION:

Here $\vec{E} = [3.1 \cos(1.8\, y + 5.4 \times 10^6 t)]\, \hat{i}$.

Comparing it with standard equation,

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

we get the following answers

(a) Wave is propagating along $-\hat{j}$ direction i.e. negative y direction because coefficient of y is positive

(b) Using $k = \frac{2\pi}{\lambda}$; $\lambda = \frac{2\pi}{k} = \frac{2\pi}{1.8} = 3.5\text{m}$

(c) Frequency, $\nu = \frac{c}{\lambda} = \frac{3 \times 10^8}{3.5} = 86 \text{ MHz}$

(d) $c = \frac{E_0}{B_0}$ or $B_0 = \frac{E_0}{c} = \frac{3.1}{3 \times 10^8} = 10\text{nT}$

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

[E is along $\hat{i}$, c is along $-\hat{j}$, c is in direction of $\vec{E} \times \vec{B}$
$-\hat{j} = \hat{i} \times \hat{k}$ $\therefore$ $\vec{B}$ is along $\hat{k}$]

$$= 10\text{nT} (\cos 1.8y \text{ rad m}^{-1} + 5.4 \times 10^6 \text{ rad s}^{-1})\, \hat{k}$$

EXAMPLE 5

Accelerating charges radiate electromagnetic waves. Calculate the wavelength of radiation produced by a proton moving in a circle of radius R perpendicular to a magnetic field of magnitude B.

SOLUTION:

For the proton, $\Sigma F = ma$ yields

$$qvB \sin 90.0° = \frac{mv^2}{R}$$

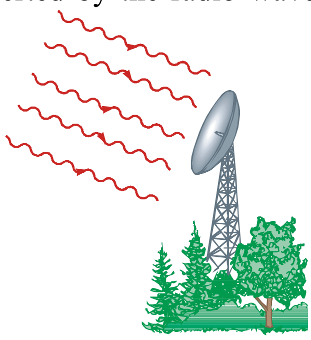
The period of the proton's circular motion is therefore: $T = \frac{2\pi R}{v} = \frac{2\pi m}{qB}$

The frequency of the proton's motion is, $f = \frac{1}{T}$

The charge will radiate electromagnetic waves at this frequency, with $\lambda = \frac{c}{f} = cT = \frac{2\pi mc}{qB}$.

EXAMPLE 6

A dish antenna having a diameter of 20.0 m receives (at normal incidence) a radio signal from a distant source, as shown in Figure. The radio signal is a continuous sinusoidal wave with amplitude $E_{max} = 0.200\ \mu\text{V/m}$. Assume the antenna absorbs all the radiation that falls on the dish. (a) What is the amplitude of the magnetic field in this wave? (b) What is the intensity of the radiation received by this antenna? (c) What is the power received by the antenna? (d) What force is exerted by the radio waves on the antenna?



SOLUTION:

(a) $B_{max} = \frac{E_{max}}{c} = 6.67 \times 10^{-16}\text{T}$

(b) $S_{av} = \frac{E_{max}^2}{2\mu_0 c} = 5.31 \times 10^{-17}\text{ W/m}^2$

(c) $P = S_{av}A = 1.67 \times 10^{-14}\text{ W}$

(d) $F = PA = \left(\frac{S_{av}}{c}\right) A = 5.56 \times 10^{-23}\text{N}$

($\cong$ the weight of 3000 H atoms)

QUESTION BANK

EXERCISE-1 (LEVEL-1)

SECTION - 1 (VOCABULARY BUILDER)

Choose one correct response for each question.
For Q.1-Q.3 : Match the column I with column II.

Q.1

Column I	Column II
(a) $\oint E_i dA = \frac{Q}{\varepsilon_0}$	(a) Faraday's law
(b) $\oint B_i dA = 0$	(b) Ampere-Maxwell law
(c) $\oint E_i d\ell = -\frac{d\phi_B}{dt}$	(c) Gauss law for electricity
(d) $\oint B_i d\ell = \mu_0 i_c + \mu_0 \varepsilon_0 \frac{d\phi_E}{dt}$	(d) Gauss law for magnetism

(A) (a) – (iv), (b) – (iii), (c) – (ii), (d) – (i)
(B) (a) – (iii), (b) – (ii), (c) – (i), (d) – (iv)
(C) (a) – (iii), (b) – (iv), (c) – (i), (d) – (ii)
(D) (a) – (i), (b) – (ii), (c) – (iii), (d) – (iv)

Q.2

Column I	Column II
(a) Radio	(i) 54 MHz
(b) Amplitude modulated	(ii) 88 MHz-108 MHz
(c) Short wave bands	(iii) 530 MHz to 1710 MHz
(d) TV wave	(iv) 500 kHz to 1000 MHz
(e) Frequency modulated	(v) 54 MHz-890 MHz

(A) (a)-(iii), (b)-(i), (c)-(v), (d)-(ii), (e)-(iv)
(B) (a)-(i), (b)-(v), (c)-(ii), (d)-(iii), (e)-(iv)
(C) (a)-(iv), (b)-(i), (c)-(v), (d)-(ii), (e)-(iii)
(D) (a)-(iv), (b)-(iii), (c)-(i), (d)-(v), (e)-(ii)

Q.3

Column I	Column II
(a) Radio	(i) 1mm to 700 nm
(b) Microwave	(ii) > 0.1 m
(c) Infrared	(iii) 0.1m to 1mm
(d) Light	(iv) 700nm to 400nm

(A) (a) – (iii), (b) – (ii), (c) – (i), (d) – (iv)
(B) (a) – (ii), (b) – (iii), (c) – (iv), (d) – (i)
(C) (a) – (ii), (b) – (iii), (c) – (i), (d) – (iv)
(D) (a) – (i), (b) – (iv), (c) – (iii), (d) – (ii)

SECTION - 2 (BASIC CONCEPTS BUILDER)

For Q.4 to Q.8 : Choose one word for the given statement from the list.

γ-rays, Radio waves, Polarised, Electric field, Inconsistency, Ampere's circuital law, Lower

Q.4 A magnetic field changing with time give rise to ______.

Q.5 While applying the ____ law to find magnetic field at a point outside a capacitor connected to a time-varying current, Maxwell notices an ____ in the Ampere's circuital law.

Q.6 The broad spectrum of electromagnetic waves, stretching from ____ to ____.

Q.7 Infrared waves frequencies are _____ than those of visible light.

Q.8 Electromagnetic waves are _____ can be easily seen in the responses of a portable AM radio to a broadcasting station.

SECTION - 3 (ENHANCE PROBLEM SOLVING SKILLS)

Choose one correct response for each question.

PART 1 DISPLACEMENT CURRENT

Q.9 A parallel plate capacitor with plate area A and separation between the plated d, is charged by a constant current i, consider a plane surface of area A/4 parallel to the plates and drawn symmetrically between the plates what is the displacement current through this area.

(A) i (B) 2i
(C) i/4 (D) i/2

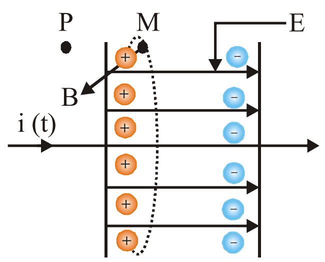
Q.10 The charge on a parallel plate capacitor varies as $q = q_0 \cos 2\pi\nu t$. The plates are very large and close together (area = A, separation = d). The displacement current through the capacitor is

(A) $q_0\, 2\pi\nu \sin\pi\nu t$ (B) $-q_0\, 2\pi\nu \sin 2\pi\nu t$
(C) $q_0\, 2\pi \sin\pi\nu t$ (D) $q_0\, \pi\nu \sin 2\pi\nu t$

Q.11 The total current passing through any surface, of which the closed loop is the perimeter, is –

(A) sum of conduction current and displacement current.
(B) difference of conduction current and displacement current.
(C) product of conduction current and displacement current.
(D) fraction of conduction current and displacement current.

Q.12 In the given figure, a magnetic field (say at point M) between the plates of the capacitor to be the same as that just –



(A) outside at P (B) between the plates
(C) above the plates (D) down the plates

Q.13 If a variable frequency ac source is connected to a capacitor then with decrease in frequency the displacement current will –

(A) increase
(B) decrease
(C) remains constant
(D) first decrease then increase.

Q.14 The charging current for a capacitor is 1 A then what is the displacement current ?

(A) 1 A (B) 0.5 A
(C) 0 (D) 2 A

Q.15 Displacement current goes through the gap between the plates of a capacitor when the charge on the capacitor –

(A) is changing with time.
(B) decreases.
(C) does not change.
(D) decreases to zero.

PART 2 ELECTROMAGNETIC WAVES

Q.16 The electromagnetic waves do not transport

(A) Energy (B) Charge
(C) Momentum (D) Information

Q.17 If E and B be the electric and magnetic field of E.M. wave then the direction of propagation of E.M. wave is along the direction.

(A) $\vec{E}$ (B) $\vec{B}$
(C) $\vec{E} \times \vec{B}$ (D) $\vec{B} \times \vec{E}$

Q.18 Which of the following pairs of space and time varying E and B fields would generate a plane electromagnetic wave travelling in (–Z) direction-

(A) E_x, B_y (B) E_y, B_x
(C) E_x, B_y (D) E_y, B_x

Q.19 Choose the wrong statement for E.M. wave. They-
(A) Are Transverse
(B) Travels in free space with the speed of light
(C) Are produced by accelerated charges
(D) Travels with same speed in all medium

Q.20 Light is an electromagnetic wave. Its speed in vacuum is given by the expression

(A) $\sqrt{\mu_o \varepsilon_o}$ (B) $\sqrt{\frac{\mu_o}{\varepsilon_o}}$
(C) $\sqrt{\frac{\varepsilon_o}{\mu_o}}$ (D) $\frac{1}{\sqrt{\mu_o \varepsilon_o}}$

Q.21 The electric field of an electromagnetic wave travelling through vacuum is given by the equation $E = E_0 \sin(kx - \omega t)$. The quantity that is independent of wavelength is –
(A) $k\omega$ (B) k/ω
(C) $k^2\omega$ (D) ω

Q.22 A plane electromagnetic wave travels in vacuum along z-direction. If the frequency of the wave is 40 MHz then its wavelength is –
(A) 5m (B) 7.5 m
(C) 8.5 m (D) 10 m

Q.23 A plane electromagnetic wave is incident on a material surface. The wave delivers momentum p and energy E. Then –
(A) $p \neq 0, E \neq 0$ (B) $p = 0, E = 0$
(C) $p = 0, E \neq 0$ (D) $p \neq 0, E = 0$

Q.24 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 equation 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

Q.25 A charged particle oscillate about its mean equilibrium position with a frequency of 10^9 Hz. The frequency of electromagnetic waves produced by the oscillator is –
(A) 10^6 Hz (B) 10^7 Hz
(C) 10^8 Hz (D) 10^9 Hz

Q.26 The amplitude of an electromagnetic wave in vacuum is doubled with no other changes made to the wave. As a result of this doubling of the amplitude, which of the following statement is correct?
(A) The speed of wave propagation changes only.
(B) The frequency of the wave changes only.
(C) The wavelength of the wave changes only.
(D) None of these.

Q.27 An electromagnetic wave propagating along north has its electric field vector upwards. Its magnetic field vector point towards –
(A) north (B) east
(C) west (D) downwards

Q.28 The ratio of amplitude of magnetic field to the amplitude of electric field for an electromagnetic wave propagating in vacuum is equal to –
(A) the speed of light in vacuum.
(B) reciprocal of speed of light in vacuum.
(C) the ratio of magnetic permeability to the electric susceptibility of vacuum.
(D) unity.

PART 3 ELECTROMAGNETIC SPECTRUM

Q.29 TV transmission is possible by-
(A) Ground wave (B) Sky wave
(C) space wave (D) None

Q.30 The range of wavelength of the visible light is
(A) 10 Å to 100 Å
(B) 4,000 Å to 7,000 Å
(C) 8,000 Å to 10,000 Å
(D) 10,000 Å to 15,000 Å

Q.31 Which radiation in sunlight, causes heating effect
(A) Ultraviolet (B) Infrared
(C) Visible light (D) All of these

Q.32 Electromagnetic radiation of highest frequency is
(A) Infrared radiations (B) Visible radiation
(C) Radio waves (D) γ-rays

Q.33 Which of the following shows green house effect
(A) Ultraviolet rays (B) Infrared rays
(C) X-rays (D) None of these

Q.34 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

Q.35 In which one of the following regions of the electromagnetic spectrum will the vibrational motion of molecules give rise to absorption
(A) Ultraviolet (B) Microwaves
(C) Infrared (D) Radio waves

Q.36 TV waves have a wavelength range of 1-10 meter. Their frequency range in MHz is –
(A) 30-300 (B) 3-30
(C) 300-3000 (D) 3-3000

Q.37 A signal emitted by an antenna from a certain point can be received at another point of the surface in the form of –
(A) Sky wave (B) Ground wave
(C) Sea wave (D) Both (A) and (B)

Q.38 Infrared waves are produced by –
(A) hot bodies and molecules.
(B) cold bodies and molecules.
(C) neither hot nor cold.
(D) both (A) and (B).

Q.39 I. Ultraviolet rays wavelength ranging about 4×10^{-7}m (400 nm) down to 6×10^{-10}m (0.6 nm).
II. UV radiation is produced by special lamps and very hot bodies.
III. The sun is an important source of ultraviolet light.
IV. Most of the UV rays absorbed in the ozone layer in the atmosphere at an altitude of about 40-50 km.
Which of the following statements are correct.
(A) I, II and III (B) II, III and IV
(C) I, III and IV (D) All of these

Q.40 In the electromagnetic spectrum, X-ray region lies –
(A) beyond the microwave region.
(B) above the ultraviolet region
(C) beyond the UV region
(D) above the infrared ray region.

Q.41 The part of the spectrum of the electromagnetic radiation used to cook food is –
(A) ultraviolet rays (B) cosmic rays
(C) X-rays (D) microwaves

Q.42 Which of the following electromagnetic wave is used in high precision application like LASIK eye surgery?
(A) Microwave (B) Ultraviolet rays
(C) Gamma rays (D) X-rays

Q.43 The waves used by artificial satellites for communication is –
(A) microwaves (B) infrared waves
(C) radio waves (D) X-rays

Q.44 If v_g, v_X and v_m are the speeds of gamma rays, X-rays and microwaves respectively in vacuum, then –
(A) $v_g < v_X < v_m$ (B) $v_g > v_X > v_m$
(C) $v_g > v_X < v_m$ (D) $v_g = v_X = v_m$

Q.45 A microwave and an ultrasonic sound wave have the same wavelength. Their frequencies are in the ratio (approximately).
(A) 10^2 (B) 10^4
(C) 10^6 (D) 10^8

EXERCISE-2 (LEVEL-2)

Choose one correct response for each question.

Q.1 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

Q.2 The intensity of light from a source is $(500/\pi)$ W/m^2. Find the amplitude of electric field in this wave-
(A) $\sqrt{3} \times 10^2$ N/C (B) $2\sqrt{3} \times 10^2$ N/C
(C) $\frac{\sqrt{3}}{2} \times 10^2$ N/C (D) $2\sqrt{3} \times 10^1$ N/C

Q.3 In a EM wave the amplitude of electric field is 10 V/m. The frequency of wave is 5×10^4 Hz. The wave is propogating along Z-axis. Then the average energy density of Magnetic field is-
(A) 2.21×10^{-10} J/m^3 (B) 2.21×10^{-8} J/m^3
(C) 2×10^{-8} J/m^3 (D) 2×10^{-10} J/m^3

Q.4 Elecromagnetic waves travel in a medium with a speed of 2×10^8 m/s. The relative permeability of the medium is 1. What is the relative permittivity of the medium –
(A) 2.25 (B) 1.25
(C) 3.25 (D) 0.25

Q.5 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) 36.5 m (B) 40.5 m
(C) 42.3 m (D) 50.9 m

Q.6 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) 4×10^{-6} T (B) 6×10^{-8} T
(C) 9×10^{-9} T (D) 11×10^{-11} T

Q.7 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

Q.8 The sun light strikes the upper atmosphere of earth with intensity 1.38 Kw/m^2. The peak value of electric field at that point will be-
(in kilovolt/meter)
(A) 2.04 (B) 4.08
(C) 8.16 (D) 1.02

Q.9 The ratio of the pressure exerted by electromagnetic waves on reflecting surface and the absorbing surface will be -
(A) 2 : 1 (B) 1 : 2
(C) 3 : 1 (D) 1 : 3

Q.10 An electromagnetic wave in vacuum has the electric and magnetic field $\vec{E}$ and $\vec{B}$, which are always perpendicular to each other. The direction of polarization is given by $\vec{X}$ and that of wave propagation by $\vec{k}$. Then
(A) $\vec{X} \parallel \vec{B}$ & $\vec{k} \parallel \vec{B} \times \vec{E}$ (B) $\vec{X} \parallel \vec{E}$ & $\vec{k} \parallel \vec{E} \times \vec{B}$
(C) $\vec{X} \parallel \vec{B}$ & $\vec{k} \parallel \vec{E} \times \vec{B}$ (D) $\vec{X} \parallel \vec{E}$ & $\vec{k} \parallel \vec{B} \times \vec{E}$

Q.11 I. Maxwell's equations that electric and magnetic fields in an electromagnetic wave are perpendicular to each other and to the direction of propagation.
II. The electric field inside the plates of the capacitor is directed perpendicular to the plates.
III. The magnetic field due to displacement current is along the perimeter of a circle parallel to the capacitor plates. So, B and E are perpendicular in this case.
Which of the above statements is/are correct?
(A) I and II (B) II and III
(C) I and III (D) All of these

Q.12 A radio can tune to any station in 7.5 MHz to 12MHz band. The corresponding wavelength band is –
(A) 40 m to 25 m (B) 30 m to 25 m
(C) 25 m to 10 m (D) 10 m to 5 m

Q.13 A plane electromagnetic wave of frequency 25MHz travels in free space along x-direction. At a particular point in space and time, electric $E = 6.3\ V\ m^{-1}$. The magnitude of magnetic field B at this point is –
(A) 1.2×10^{-6} T (B) 1.2×10^{-8} T
(C) 2.1×10^{-6} T (D) 2.1×10^{-8} T

Q.14 Radiations of intensity $0.5\ Wm^{-2}$ are striking a metal plate. The pressure (in Nm^{-2})on the plate
(A) 0.166×10^{-8} (B) 0.332×10^{-8}
(C) 0.111×10^{-8} (D) 0.083×10^{-8}

Q.15 An electromagnetic radiation has an energy of 13.2 keV. Then the radiation belongs to the region
(A) visible light (B) ultraviolet
(C) infrared (D) X-ray

Q.16 I. Wavelength of microwaves is greater than that of ultraviolet rays.
II. The wavelength of infrared rays is lesser than that of ultraviolet rays.
III. The wavelength of microwave is lesser than that of infrared rays.
IV. Gamma rays has shortest wavelength in the electromagnetic spectrum.
Choose the correct option from the given options
(A) I and II are true (B) II and III are true
(C) III and IV are true (D) I and IV are true

Q.17 I. The total current i is the sum of the condensation current denoted by i_c, and the displacement current denoted by $i_d(t) = \varepsilon_0 (d\phi_E/dt)$.

So, $i = i_e + i_d = i_c + \varepsilon_0 \dfrac{d\phi_\varepsilon}{dt}$

II. Outside the capacitor plates, we have only conduction current $i_c = i$ and no displacement current, $i_d = 0$
III. Inside the capacitor, there is no conduction current $i_c = 0$ and there is only displacement current, so that $i_d = i$.
Which of the above statements is/are correct?
(A) I and II (B) II and III
(C) I and III (D) All of these

EXERCISE-3 (LEVEL-3)

Choose one correct response for each question.

Q.1 The rms value of the electric field of the light coming from the sun is 720 N/C. The average total energy density (in Jm^{-3}) of the electromagnetic wave
(A) 3.3×10^{-3} (B) 4.58×10^{-6}
(C) 6.37×10^{-9} (D) 81.35×10^{-12}

Q.2 Light with an energy flux of $18\ W\ cm^{-2}$ falls on a non-reflecting surface at normal incidence. If the surface has an area of $20\ cm^2$, the average force exerted on the surface during a 30 minute time span is –
(A) 2.1×10^{-6} N (B) 1.2×10^{-6} N
(C) 1.2×10^{6} N (D) 2.1×10^{6} N

Q.3 Assume a bulb of efficiency 2.5% as a point source. The peak values of electric and magnetic fields produced by the radiation coming from a 100W bulb at a distance of 3m is respectively
(A) $2.5\ Vm^{-1}$, 3.6×10^{-8} T
(B) $4.2\ Vm^{-1}$, 2.8×10^{-8} T
(C) $4.08\ Vm^{-1}$, 1.36×10^{-8} T
(D) $3.6\ Vm^{-1}$, 4.2×10^{-8} T

Q.4 The magnetic field of a beam emerging from a filter facing a flood light as given by
$B = 12 \times 10^{-8} \sin(1.20 \times 10^7 z - 3.60 \times 10^{15} t)$T.
The average intensity of the beam is –
(A) $1.71\ Wm^{-2}$ (B) $2.1\ Wm^{-2}$
(C) $3.2\ Wm^{-2}$ (D) $2.9\ Wm^{-2}$

Q.5 The electric field of a plane electromagnetic wave varies with time of amplitude $2\ Vm^{-1}$ propagating along z-axis. The average energy density of the magnetic field (in Jm^{-3}) is
(A) 13.29×10^{-12} (B) 8.86×10^{-12}
(C) 17.72×10^{-12} (D) 4.43×10^{-12}

Q.6 The magnetic field in a travelling electromagnetic wave has a peak value of 20 nT. The peak value of electric field strength is –
(A) 3V/m (B) 6V/m
(C) 9V/m (D) 12 V/m

Q.7 The frequency of electromagnetic wave which is best suitable to observe a particle of radius 3×10^{-4} cm is of the order of –
(A) 10^{15} Hz (B) 10^{14} Hz
(C) 10^{13} Hz (D) 10^{12} Hz

Q.8 Light with an energy flux of 20 W/cm^2 falls on a non-reflecting surface at normal incidence. If the surface has an area of 30 cm^2. the total momentum delivered (for complete absorption) during 30 minutes is
(A) 36×10^{-5} kg m/s. (B) 36×10^{-4} kg m/s.
(C) 108×10^{4} kg m/s. (D) 1.08×10^{7}kg m/s.

For Q.9-Q.11
The magnetic field in a plane electromagnetic wave is given by
$B_y = 2 \times 10^{-7} \sin (0.5 \times 10^3 x + 1.5 \times 10t)$ T.

Q.9 What is the wavelength of the wave ?
(A) 12.6 cm (B) 1.26 cm
(C) 1.26 m (D) 6.12 m

Q.10 What is the, frequency of the wave ?
(A) 2.39 GHz (B) 23.9 GHz
(C) 23.9 GHz (D) 20.3 MHz

Q.11 Write an expression for the electric field ?
(A) $E_y = 60 \sin (0.5 \times 10^3 x + 1.5 \times 10^{11} t)$V/m
(B) $E_x = 60 \sin (0.5 \times 10^3 x + 1.5 \times 10^{11} t)$V/m
(C) $E_z = 60 \sin (0.5 \times 10^3 x + 1.5 \times 10^{11} t)$V/m
(D) $E_y = 60 \cos (0.5 \times 10^3 x + 1.5 \times 10^{11} t)$V/m

Q.12 A perfectly reflecting mirror has an area of 1cm^2. Light energy is allowed to fall on it for 1h at the rate of 10 W cm^{-2}. The force that acts on the mirror is –
(A) 9.35×10^{-8} N (B) 6.7×10^{-8} N
(C) 1.34×10^{-7} N (D) 2.4×10^{-4} N

ANSWER KEY

CHECK UP 1

(1) Energy moves. No matter moves. You could say that electric and magnetic fields move, but it is nicer to say that the fields at one point stay at that point and oscillate. The fields vary in time, like sports fans in the grandstand when the crowd does the wave. The fields constitute the medium for the wave, and energy moves.

(2) No. If a single wire carries DC current, it does not emit electromagnetic waves. In this case, there is a constant magnetic field around the wire. Alternately, if the cable is a coaxial cable, it ideally does not emit electromagnetic waves even while carrying AC current.

(3) Acceleration of electric charge.

(4) The changing magnetic field of the solenoid induces eddy currents in the conducting core. This is accompanied by I^2R conversion of electrically-transmitted energy into internal energy in the conductor.

(5) **No.** Static electricity is just that: static. Without acceleration of the charge, there can be no electromagnetic wave.

(6) 3.33 $\mu J/m^3$

(7) 307 $\mu W/m^2$

(8) $I = 7.96\ W/m^2$, $u = 26.5\ nJ/m^3$
(a) 13.3 nJ/m^3 (b) 13.3 nJ/m^3 (c) 7.96 W/m^2

(9) 83.3 nPa

EXERCISE - 1

(1) **(C)** **(2) (D)** **(3) (C)**

(4) Electric field

(5) Ampere's circuital law, inconsistency

(6) γ-rays, radio waves

(7) Lower

(8) Polarised.

EXERCISE 1 (SECTION–3)

Q	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33
A	C	B	A	A	B	A	A	B	C	B	D	D	B	B	A	A	D	D	B	B	C	B	B	D	B
Q	34	35	36	37	38	39	40	41	42	43	44	45													
A	A	B	A	D	A	D	B	D	B	A	D	C													

EXERCISE–2

Q	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
A	D	B	A	A	A	B	A	D	A	B	D	A	D	A	B	D	D

EXERCISE–3

Q	1	2	3	4	5	6	7	8	9	10	11	12
A	B	B	C	A	B	B	A	B	B	C	C	B