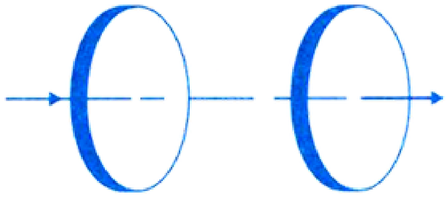
EXERCISE QUESTIONS

CHAPTER - 8 ELECTROMAGNETIC WAVES

8.1 Figure 8.6 shows a capacitor made of two circular plates each of radius 12 cm, and separated by 5.0 cm. The capacitor is being charged by an external source (not shown in the figure). The charging current is constant and equal to 0.15A.
(a) Calculate the capacitance and the rate of change 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.



Ans - (a) Capacitance of the parallel plate capacitor
Charge on each plate, q = CV

$$C = \frac{\varepsilon_0 A}{d} = \frac{8.85\times10^{-12}\times\pi\times(12\times10^{-2})^2}{5\times10^{-3}}$$

$$C = 80.1\times10^{-12}\ \text{F} = 80.1\ \text{pF}$$

We know $Q = CV$

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

So, $\frac{dV}{dt} = \frac{I}{C} = \frac{0.15}{80.1\times10^{-12}} = 1.875\times10^{9}\ \text{V s}^{-1}$

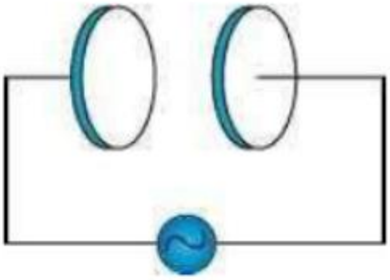
(b) The conduction current and the displacement current flowing across the plates are identical. The displacement current, id, is therefore 0.15 A.

(c) Yes

At each plate of the capacitor, Kirchhoff's first rule is applicable as long as we use the total of conduction and displacement to calculate current.

8.2 A parallel plate capacitor (Fig. 8.7) made of circular plates each of radius R = 6.0 cm has a capacitance C = 100 pf. The

capacitor is connected to a 230 V ac supply with a (angular) frequency of 300 rad s–1 .
(a) What is the rms value of the conduction current?
(b) Is the conduction current equal to the displacement current?
(c) Determine the amplitude of B at a point 3.0 cm from the axis between the plates.



Ans - Each circular plate's radius is R = 6.0 cm, or 0.06 m.

A parallel plate capacitor's capacitance is C = 100 pF = 100x 10-12 F.

A supply voltage of 230 volts.

Here $V_{rms} = 230\text{ V}, C = 100\,pF$
$= 100 \times 10^{-12} = 10^{-10}\text{ F}$
$\omega = 300\text{ rad s}^{-1}$

(*a*) Using $I_{rms} = \frac{V_{rms}}{X_C}$, we get,

$$I_{rms} = \frac{V_{rms}}{\frac{1}{C\omega}} = V_{rms} \times C\omega$$
$$= 230 \times 10^{-10} \times 300$$
$$= 69 \times 10^{-7} = 6{\cdot}9\ \mu\text{A}.$$

(*b*) Yes, because

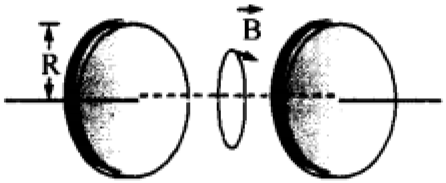
$$I_d = \epsilon_0 \frac{d\phi_E}{dt} = \frac{\epsilon_0\, d(EA)}{dt} = \frac{\epsilon_0 A}{d}\frac{dV}{dt} = C\frac{dV}{dt}$$

$$\left(\because C = \frac{\epsilon_0 A}{d}\right)$$

But $\frac{dV}{dt} = \frac{I_C}{C}$ $\therefore$ $I_d = C \times \frac{I_C}{C}$

$= I_C$ (Conduction Current)

(*c*) Consider the figure given below



Using Ampere's Circuital law we get

$$\oint \vec{B}.\vec{dl} = \epsilon_0 \mu_0 \oint \frac{\partial \vec{E}}{\partial t}.d\vec{S}$$

$$\text{or } B \times 2\pi r = \mu_0 \epsilon_0 \frac{dE}{dt} \pi r^2$$

$$\therefore \quad B = \frac{\mu_0 \epsilon_0 r}{2} \frac{dE}{dt} \quad \quad ...(i)$$

$$\text{But} \quad E = \frac{\sigma}{\epsilon_0} = \frac{q}{A \epsilon_0}$$

$$\therefore \quad \frac{dE}{dt} = \frac{\frac{dq}{dt}}{A \epsilon_0} = \frac{I}{\pi R^2 \epsilon_0}$$

8.3 What physical quantity is the same for X-rays of wavelength 10–10m, red light of wavelength 6800 Å and radiowaves of wavelength 500m?

Ans - For all wavelengths, the speed of light in a vacuum (3 108 m/s) remains constant. It is unaffected by the vacuum's wavelength.

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 field vector E and the magnetic field vector B exhibit fluctuations in electromagnetic waves that are both perpendicular to the direction of wave propagation and perpendicular to one another. Due to the electromagnetic wave's z-direction of travel, E and B exhibit their variation in the x-y plane.

$$\text{Using } c = \lambda\nu, \text{ we get } \lambda = \frac{c}{\nu}$$

$$i.e. \quad \lambda = \frac{3\times10^8}{30\times10^6} = 10 \text{ m}$$

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

Ans - The least frequency that a radio may receive is v1 = 7.5 MHz= 7.5 x106 Hz.

The highest frequency is 2 = 12 MHz, or 12 x106 Hz.

Light-speed formula: c = 3x 108 m/s

$$, \boxed{\lambda_1 = \frac{c}{v_1}} = \frac{3 \times 10^8}{7.5 \times 10^6} = 40 \text{ m}$$

$$\lambda_2 = \frac{c}{v_2} = \frac{3 \times 10^8}{12 \times 10^6} = 25 \text{ m}$$

8.6 A charged particle oscillates about its mean equilibrium position with a frequency of 109 Hz. What is the frequency of the electromagnetic waves produced by the oscillator?

Ans - The oscillator generates electromagnetic waves at 109 Hz, the same frequency as a charged particle oscillating about its mean location.

8.7 The amplitude of the magnetic field part of a harmonic electromagnetic wave in vacuum is B0 = 510 nT. What is the amplitude of the electric field part of the wave?

Ans - Amplitude of magnetic field of an electromagnetic wave in a vacuum

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

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

$= 153 \text{ N C}^{-1}$.

8.8 Suppose that the electric field amplitude of an electromagnetic wave is E0 = 120 N/C and that its frequency is v = 50.0 MHz.

(a) Determine, B0 ,ω, k, and λ.

(b) Find expressions for E and B.

Ans - 120 N/C is the electric field's amplitude.

Source frequency: v = 50.0 MHz, or 50 x 106 Hz

Light-speed formula: c = 3 x 108 m/s

(a) The strength of the magnetic field is given as

$$B_0 = \frac{E}{c} = \frac{120}{3 \times 10^8}$$

$$= 4 \times 10^{-7} \text{ T}$$

i.e. $B_0 = 400\, n\text{T}$.

(ii) $\omega = 2\pi\nu$

$$= 2 \times \pi \times 50 \times 10^6$$

$$= 3{\cdot}14 \times 10^8 \text{ rad s}^{-1}$$

(iii) $c = \lambda\nu$

i.e. $\lambda = \frac{c}{\nu} = \frac{3 \times 10^8}{50 \times 10^6} = 6 \text{ m}$

(iv) $k = \frac{\omega}{c} = \frac{3{\cdot}14 \times 10^8}{3 \times 10^8}$

$$= 1{\cdot}05 \text{ rad m}^{-1}$$

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

$$= 120 \sin(1{\cdot}05x - 3{\cdot}14 \times 10^8 \times t)\, \hat{j},$$

with usual units and

$$\vec{B} = B_0 \times \sin(kx - \omega t)\, \hat{k}$$

$$= 400 \times 10^{-7} \sin(1{\cdot}05x - 3{\cdot}14 \times 10^8 \times t)\, \hat{k}$$

with usual units.

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

Ans - The photon with the specified energy is released when an atom transitions between energy levels, and the energy of the photon that is released corresponds to the energy difference between the energy levels between which the transition occurred.
as in the case of photon energy

(*b*) For X-rays, let $\lambda = 1$ nm $= 10^{-9}$ m, then

$$E = \frac{1{\cdot}24\times10^{-6}}{10^{-9}} = 1{\cdot}24 \times 10^{3}\ eV$$

$$= 1240\ eV$$

(*c*) For visible light, let $\lambda = 1\mu$m $= 10^{-6}$ m, then

$$E = \frac{1{\cdot}24\times10^{-6}}{10^{-6}} = 1{\cdot}24\ eV$$

(*d*) For microwaves, let $\lambda = 1$ cm $= 10^{-2}$ m, then

$$E = \frac{1{\cdot}24\times10^{-6}}{10^{-2}} = 1{\cdot}24 \times 10^{-4}\ eV$$

(*e*) For radiowaves, let $\lambda = 1$ km $= 1000$ m, then

$$E = \frac{1{\cdot}24\times10^{-6}}{1000} = 1{\cdot}24 \times 10^{-9}\ eV.$$

$$E = h\nu \text{ we get } E = \frac{hc}{\lambda}$$

For $\lambda = 1$ m, we get

$$E = \frac{(6{\cdot}63\times10^{-34})(3\times10^{8})}{1\times1{\cdot}6\times10^{-19}}$$

$$= 1{\cdot}24 \times 10^{-6}\, eV.$$

⇒ Energy for other wavelengths can be worked out from the relation

$$E_\lambda = \frac{1{\cdot}24\times10^{-6}}{\lambda} eV$$

(*a*) For γ-rays, let $\lambda = 10^{-12}$ m, then

$$E = \frac{1{\cdot}24\times10^{-6}}{10^{-12}} = 1{\cdot}24 \times 10^{6}\, eV$$

$$= 1{\cdot}24\, MeV$$

8.10 In a plane electromagnetic wave, the electric field oscillates sinusoidally at a frequency of 2.0 × 1010 Hz and amplitude 48 V m–1 .

(a) What is the wavelength of the wave?

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

(c) Show that the average energy density of the E field equals the average energy density of the B field. [c = 3 × 108 m s–1.]

Ans - The electromagnetic wave's frequency is 2.0 x 1010 Hz.

Amplitude of the electric field, E0 = 48 V m

Light-speed formula: c = 3 x 108 m/s

(*a*) Using $c = \lambda\nu$, we get

$$\lambda = \frac{c}{\nu} = \frac{3\times10^8}{2\times10^{10}} = 1{\cdot}5 \times 10^{-2}\ \text{m}$$

(*b*) Using $c = \frac{E_0}{B_0}$, we get

$$B_0 = \frac{E_0}{c} = \frac{48}{3\times10^8} = 1{\cdot}6 \times 10^{-7}\ \text{T}$$

(*c*) Average energy density of the electric field,

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

and average energy density of the magnetic field,

$$U_B = \frac{B_0^2}{4\mu_0}$$

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

i.e. $\frac{E_0}{B_0} = \frac{1}{\sqrt{\mu_0\varepsilon_0}}$

Then $\frac{U_E}{U_B} = \frac{\mu_0\varepsilon_0 E_0^2}{B_0^2} = \frac{\mu_0\varepsilon_0}{\mu_0\varepsilon_0} = 1$

or $U_E = U_B$

8.11 Suppose that the electric field part of an electromagnetic wave in vacuum is
E = {(3.1 N/C) cos [(1.8 rad/m) y + (5.4 × 106 rad/s)t]} ˆi .
(a) What is the direction of propagation?
(b) What is the wavelength λ ?
(c) What is the frequency v ?
(d) What is the amplitude of the magnetic field part of the wave?
(e) Write an expression for the magnetic field part of the wave.
Ans - as per given

It is obvious from the electric field vector that the electric field is oriented in a negative x direction. As a result, the motion is in the opposite direction of y, i.e.

Here $\vec{E} = 3 \cdot 1 \cos(1 \cdot 8y + 5 \cdot 4 \times 10^6 t)\,\hat{i}$

Comparing it with standard equation

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

(*a*) $-\hat{j}$ direction *i.e.* wave travels along negative *y* direction.

(*b*) $k = 1 \cdot 8$ or $\frac{2\pi}{\lambda} = 1 \cdot 8$ or $\lambda = \frac{2\pi}{1 \cdot 8}$

$= 3 \cdot 5$ m

(*c*) $\omega = 5 \cdot 4 \times 10^6$ or $2\pi\nu = 5 \cdot 4 \times 10^6$

or $\nu = \frac{5 \cdot 4 \times 10^6}{2\pi} = 0 \cdot 86$ MHz

(*d*) $c = \frac{E_0}{B_0}$ or $B_0 = \frac{E_0}{c} = \frac{3 \cdot 1}{3 \times 10^8}$

$= 10$ nT

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

$= 10 \text{ nT} \cos(1 \cdot 8y \text{ rad m}^{-1} + 5 \cdot 4 \times 10^6 \text{ rad s}^{-1})\,\hat{k}$

8.12 About 5% of the power of a 100 W light bulb is converted to visible radiation. What is the average intensity of visible radiation (a) at a distance of 1m from the bulb?
(b) at a distance of 10 m?
Assume that the radiation is emitted isotropically and neglect reflection.

Ans - Given that only 5% of the power in the bulb is transferred to visible radiations, the bulb radiates light equally in all directions.

(*a*) Visible power = 5 W

∴ Average intensity of radiation at 1 m

$$= \frac{\text{Power}}{4\pi r^2} = \frac{5}{4 \times \pi \times 1} = 0{\cdot}4 \text{ W m}^{-2}$$

(*b*) Average intensity of radiation at 10 m

$$= \frac{\text{Power}}{4\pi r'^2} = \frac{5}{4 \times \pi \times 10^2}$$

$$= 0{\cdot}004 \text{ W m}^{-2}$$

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

Ans - At extremely high temperatures, a black body produces a continuous spectrum. We can determine the wavelength that corresponds to the radiation's peak intensity using Wien's displacement law. absolute temperature needed

Using $\lambda_m T = 0{\cdot}29$ cm K we get

$$T = \frac{0{\cdot}29}{\lambda_m} \text{K}$$

$$T = 0{\cdot}29 \text{ K for } \lambda_m = 1 \text{ cm.}$$

(*a*) For $\lambda_m = 10^{-10}$ cm, we get

$$T = \frac{0{\cdot}29}{10^{-10}} = 2{\cdot}9 \times 10^9 \text{ K.}$$

(*b*) For $\lambda_m = 1 \text{ nm} = 10^{-7}$ cm, we get

$$T = \frac{0{\cdot}29}{\lambda_m} = \frac{0{\cdot}29}{10^{-7}} = 2{\cdot}9 \times 10^6 \text{ K.}$$

(*c*) For $\lambda_m = 1\ \mu\text{m} = 10^{-4}$ cm, we get

$$T = \frac{0{\cdot}29}{10^{-4}} = 2{\cdot}9 \times 10^3 = 2900 \text{ K}$$

(*d*) For $\lambda_m = 1 \text{ m} = 100$ cm, we get

$$T = \frac{0{\cdot}29}{100} = 2{\cdot}9 \times 10^{-3} \text{ K}$$

(*e*) For $\lambda_m = 1 \text{ km} = 10^5$ cm, we get

$$T = \frac{0{\cdot}29}{10^5} = 2{\cdot}9 \times 10^{-6} \text{ K}$$

8.14 Given below are some famous numbers associated with electromagnetic radiations in different contexts in physics. State the part of the electromagnetic spectrum to which each belongs.
(a) 21 cm (wavelength emitted by atomic hydrogen in interstellar space).
(b) 1057 MHz (frequency of radiation arising from two close energy levels in hydrogen; known as Lamb shift).
(c) 2.7 K [temperature associated with the isotropic radiation filling all space-thought to be a relic of the 'big-bang' origin of the universe].
(d) 5890 Å - 5896 Å [double lines of sodium]
(e) 14.4 keV [energy of a particular transition in 57Fe nucleus associated with a famous high resolution spectroscopic method (Mössbauer spectroscopy)].

Ans - (A) Radio waves have a wavelength of 21 cm and have a frequency of almost 1445 MHz.

(b) Radio waves and electromagnetic waves both have frequencies of 1057 MHz.

(c) Wien's Law can be used to determine the wavelength of the radiation that heavenly bodies release most frequently at a particular temperature.

$$\lambda_m T = 0{\cdot}29$$

$$\text{or} \quad \lambda_m = \frac{0{\cdot}29}{T} = \frac{0{\cdot}29}{2{\cdot}7}$$

$$= 0{\cdot}09 \text{ cm} = 0{\cdot}0009 \text{ m}$$

Wavelength is of the order of 10^{-4} m *i.e.* microwave.

d) The visible region of electromagnetic waves (yellow) corresponds to this wavelength.

(e) Radiation frequency can be computed.

$$E = h\upsilon$$

$$\upsilon = \frac{E}{h} = \frac{14.4\times10^3\times1.6\times10^{-19}}{6.6\times10^{-34}} \text{ Hz}$$

$$= 3.49 \times 10^{18} \text{ Hz}$$

8.15 Answer the following questions:
(a) Long distance radio broadcasts use short-wave bands. Why?

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

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

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

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

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

Ans - (a) The ionosphere, where lower frequency radio waves, or medium waves, are absorbed, reflects electromagnetic radiation in the shortwave band. Short waves are hence appropriate for long-distance radio transmission.

(b) After frequency modulation, very high frequency (VHF) and ultra high frequency (UHF) electromagnetic waves utilised in television transmission can only be sent directly from antenna. Thus, the range is very constrained. Satellite technology is used to transmit data over large distances.

c) X-rays are absorbed by the atmosphere, while radio and visible light waves can pass through it. Therefore, optical telescopes can be used on the ground, while X-ray astronomical telescopes can only be used above the atmosphere and are therefore mounted on satellites that orbit the earth.

(d) The flimsy ozone layer filters out dangerous Y-rays, cosmic radiation, and ultraviolet radiation. The living cells are susceptible to damage from all of these high energy radiations.

As a result, maintaining a thin ozone layer above the stratosphere is essential for human survival.

(e) Without an atmosphere, daytime temperatures can increase significantly but nighttime temperatures will fall much below zero degrees Celsius. Despite the fact that there won't be a greenhouse effect, the average temperature will drop.

(f) Global nuclear war will result in dense clouds that will block the sun's rays from penetrating the entire planet. The result would be a harsh "nuclear winter."