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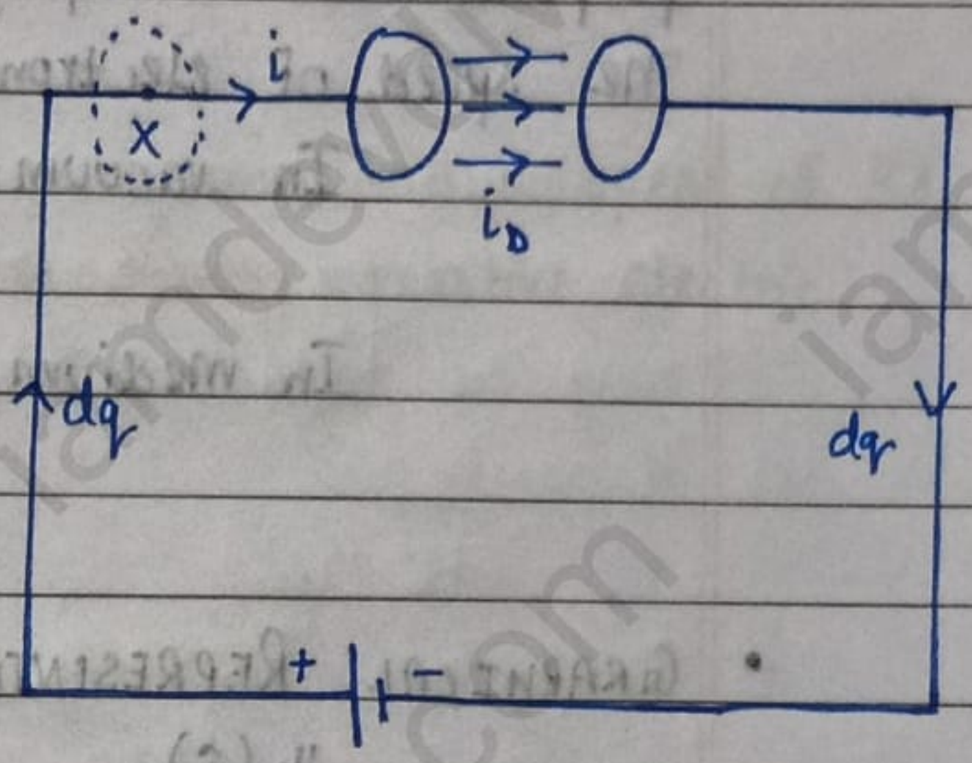
CHAPTER- 8

ELECTROMAGNETIC WAVES

☆ MAXWELL'S DISPLACEMENT CURRENT

According to Ampere's Circuital Law,

$$\oint \vec{B} \cdot d\vec{l} = \mu_0 I$$



But according to Maxwell, there is another current in the circuit which is called displacement current

$$\oint \vec{B} \cdot d\vec{l} = \mu_0 (I + I_D) \quad \text{---} \quad (1)$$

"Displacement current is that current which comes into play in the region in which the electric field and electric flux is changing with time."

We know that,

$$\phi = \frac{q}{\varepsilon_0}$$

$$\Rightarrow \frac{d\phi}{dt} = \frac{d}{dt}\left(\frac{q}{\varepsilon_0}\right)$$

$$\Rightarrow \varepsilon_0 \frac{d\phi}{dt} = \frac{dq}{dt}$$

$$\Rightarrow \varepsilon_0 \frac{d\phi}{dt} = I_D$$

$$\Rightarrow I_D = \varepsilon_0 \frac{d\phi}{dt}$$

Putting value of I_D in eq^n (1)

$$\boxed{\oint \vec{B} \cdot d\vec{l} = \mu_0 \left[I + \varepsilon_0 \frac{d\phi}{dt} \right]}$$

'Also known as Ampere - Maxwell rule'

★ ELECTROMAGNETIC WAVES [EMW]

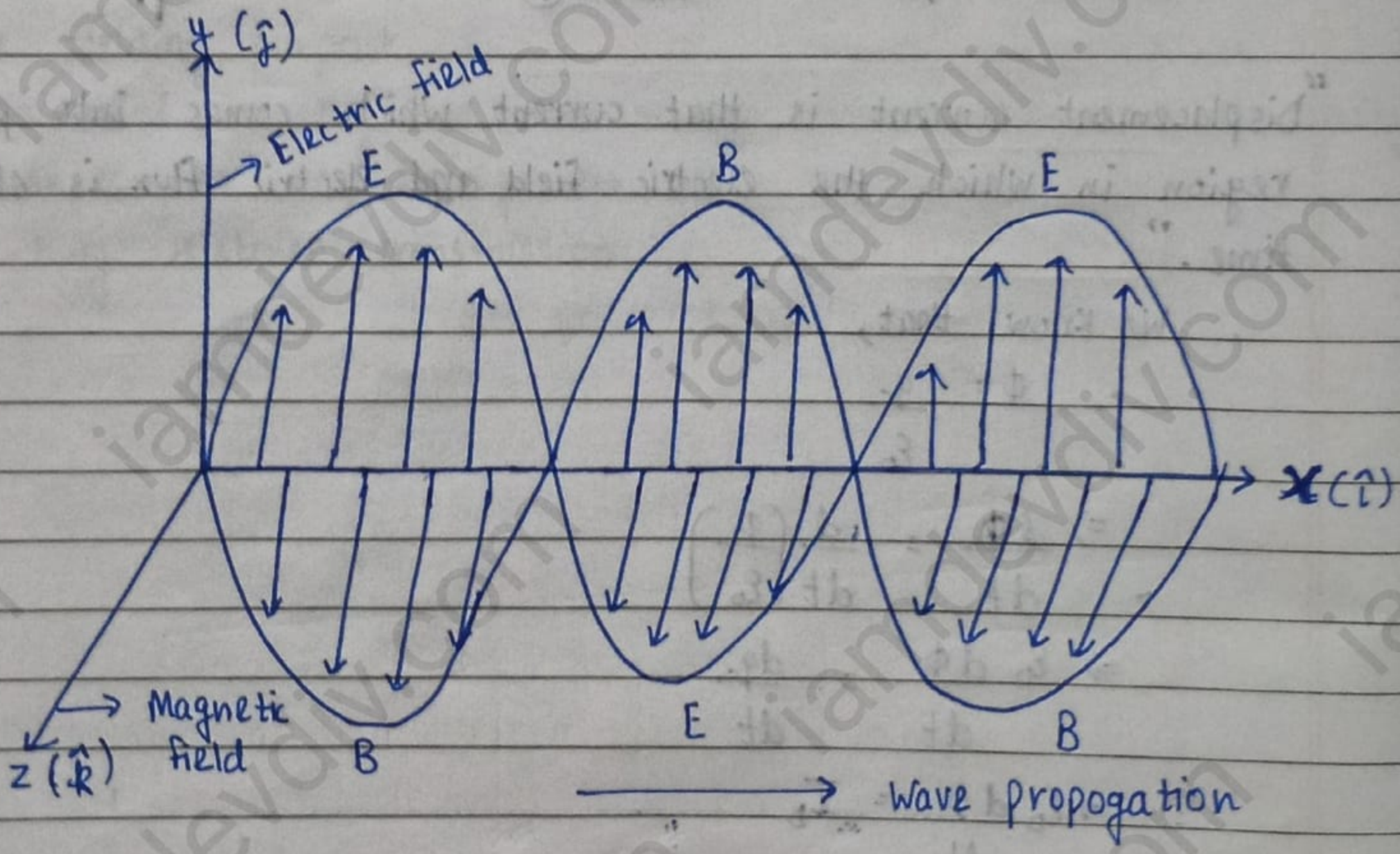
These are the waves in which electric field and magnetic field are mutually perpendicular to each other as well as they are perpendicular to propogation of wave.

The speed of electromagnetic wave is given by,

In vacuum ⇒ $v = \frac{1}{\sqrt{\mu_0 \varepsilon_0}} = 3 \times 10^8$ m/s

In medium ⇒ $v = \frac{1}{\sqrt{\mu_m \varepsilon_m}}$

- GRAPHICAL REPRESENTATION OF EMW



- PROPERTIES OF EMW

1. They are produced by accelerated or oscillating charge.
2. They do not require any medium for their propogation.
3. They travel in free space with the speed of Light.
4. The amplitude of electric field and magnetic field are related to each other by the formula, $c = \frac{E_0}{B_0}$.

5. The direction of magnetic field and electric field are always perpendicular to each other.
6. The speed of EMW in medium is less than the speed of light in vacuum.

Q An electromagnetic wave is travelling in vacuum with a speed of 3×10^8 m/s. Find its velocity in medium having relative electric and magnetic permeability 2 and 1, respectively.

Sol. $V = \frac{1}{\sqrt{\mu_0 \varepsilon_0}} = 3 \times 10^8$ m/s

$\varepsilon_r = 2$, $\mu_r = 1$

$\mu_r = \frac{\mu_m}{\mu_0} \Rightarrow \mu_m = \mu_r \mu_0$

$\varepsilon_r = \frac{\varepsilon_m}{\varepsilon_0} \Rightarrow \varepsilon_m = \varepsilon_r \varepsilon_0$

$V = \frac{1}{\sqrt{\mu_m \varepsilon_m}} = \frac{1}{\sqrt{\mu_r \mu_0 \varepsilon_r \varepsilon_0}} = \frac{1}{\sqrt{\mu_0 \varepsilon_0}} \times \frac{1}{\sqrt{\mu_r \varepsilon_m}}$

$V_m = 3 \times 10^8 \times \frac{1}{\sqrt{2 \times 1}} = \frac{3 \times 10^8}{\sqrt{2}}$ m/s Ans

Q An electromagnetic wave is travelling in a medium with a speed of 2×10^8 m/s. Relative magnetic permeability is 1. Find relative electric permittivity.

Sol. $V_m = \frac{1}{\sqrt{\mu_m \varepsilon_m}}$

$\Rightarrow 2 \times 10^8 = \frac{1}{\sqrt{\mu_r \mu_0 \varepsilon_r \varepsilon_0}}$

$\Rightarrow 2 \times 10^8 = \frac{1}{\sqrt{\mu_0 \varepsilon_0}} \times \frac{1}{\sqrt{\mu_r \varepsilon_m}}$

$\Rightarrow 2 \times 10^8 = 3 \times 10^8 = \frac{1}{\sqrt{\varepsilon_m}}$ $[\because \mu_r = 1]$

$\Rightarrow \frac{4}{9} = \frac{1}{\varepsilon_m}$

$\Rightarrow \varepsilon_m = \frac{9}{4}$ Ans

Q A plain electromagnetic wave of frequency 25 mHz travels in free space along x-axis. The $\vec{E}$ field is given by 6.3 V/m $\hat{j}$. Find magnetic field and its direction.

Sol. $C = \frac{E_0}{B_0}$

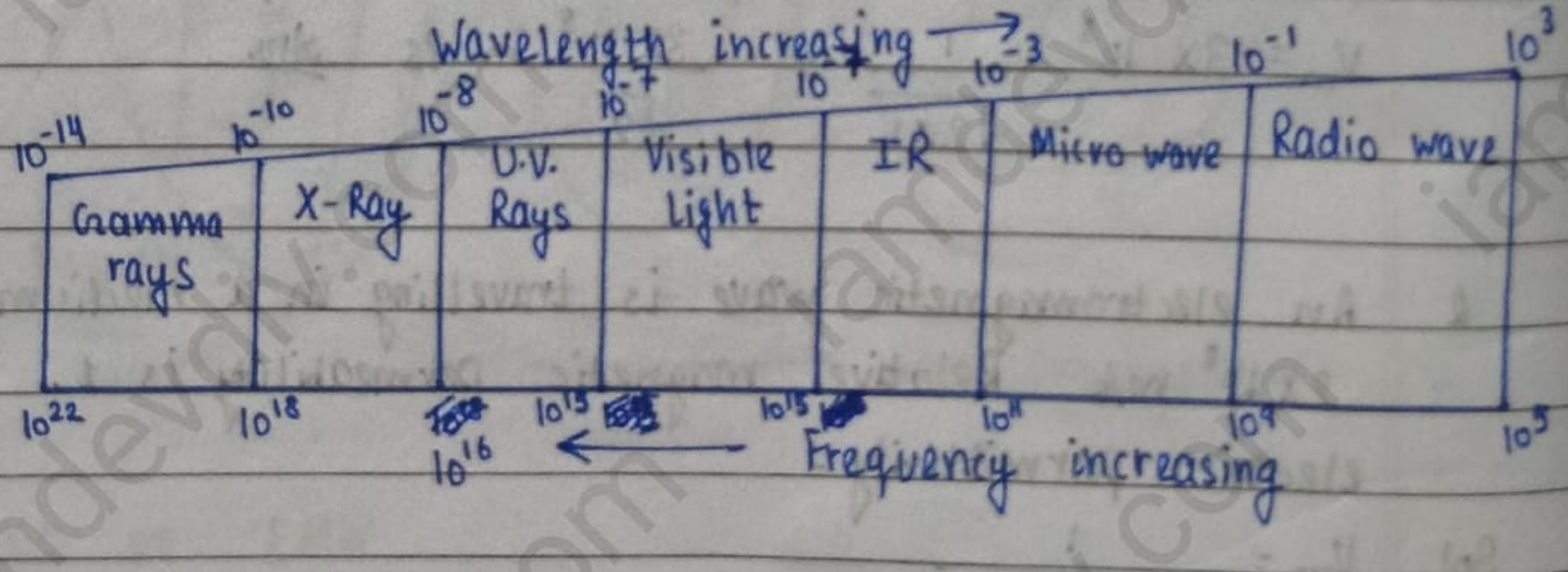
$\Rightarrow B_0 = \frac{E_0}{C} = \frac{6.3}{3\times10^8}$ (2.1)

$\Rightarrow B_0 = 2.1\times10^{-8}\ T\ \hat{k}$ Ans

★ ELECTROMAGNETIC SPECTRUM

The whole range of frequency / wavelength of electromagnetic wave arranged in one order is known as electromagnetic spectrum.

It consists of seven waves:



WAVE TYPE	W.L. IN METER	FREQUENCY (H_z)
Radio	0.3 to 6×10^2	10^9 to 5×10^5
Micro	10^{-3} to 0.3	3×10^{11} to 10^9
I.R.	8×10^{-7} to 10^{-3}	4×10^{14} to 3×10^{11}
Visible light	4×10^{-7} to 8×10^{-7}	8×10^{14} to 4×10^{14}
U.V.	6×10^{-9} to 4×10^{-7}	5×10^{16} to 8×10^{14}

X-Ray	10^{-13} to 3×10^{-8}	3×10^{21} to 1×10^{16}
Gamma	0.6×10^{-14} to 10^{-10}	5×10^{22} to 3×10^{18}

★ USES OF EMW

- **RADIO WAVE**

1. These are used in amplitude modulation.
2. These are used in frequency modulation.
3. These are used in cell phones.
4. These are used in television broadcasting.
5. It has reflection and diffraction.

- **MICRO WAVES**

1. These are used for cooking purpose in microwaves.
2. These are used in radar system. for aircraft navigation.
3. To measure the speed of ~~distance~~ vehicle or speed of cricket ball.
4. It has reflection, refraction, polarization or diffraction.

- **INFRARED RAYS [IR]**

1. These are used in physio therapy to treat muscular strain.
2. They are used in solar water heater and cooker.
3. They are used in weather forecasting.

- **VISIBLE LIGHT**

1. To see the beautiful world.
2. In movie screens or in cinema hall.
3. In lasers.

- **UV RAYS**

1. To ~~purify~~ destroy the bacteria in surgical instrument.
2. In Brglar alarm.
3. In water purifier.

4. In study of invisible writing and finger print.

- X-RAYS

1. To detect fractured bones.
2. To cure skin diseases.
3. ~~In water purifier~~. To detect explosives in the body of ~~cupid~~ Smuggler.
4. In detection of cracks of the bridge.

- GAMMA RAYS

"Cobalt-60 is the pure gamma-ray source"

1. In treatment of cancer.
2. To initiate nuclear reaction.
3. To study the structure of atomic nuclie.

Q Do electromagnetic wave carry energy and momentum?

Ans. Yes, it carries energy and momentum.

$$P = \frac{h}{\lambda} \quad [\text{Momentum}]$$

$$\text{Energy} = \frac{1}{2} \varepsilon_0 E^2$$

Q Arrange in order of increasing frequency

γ-ray, microwave, IR and UV.

Ans. Microwave < IR < UV < γ-ray

Q Arrange in order of decreasing wavelength

Microwave, IR, U.V., γ-ray

Ans. Microwave > IR > UV > γ-ray

Q Why are IR called heat waves?

Ans. When IR wares falls on some medium, it vibrates not only electrons but also the entire atom. Due to this, it increases

the internal energy and hence temperature of substance also increases. That's why, they are called heat waves.

★ EQUATION OF MAGNETIC AND ELECTRIC FIELD

$B_y = B_0 \sin(kx \pm \omega t)$

$E_z = E_0 \sin(kx \pm \omega t)$

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

(i) a) What is the wavelength

b) and frequency

(ii) Expression for electric field

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

$B_y = B_0 \sin(kx \pm \omega t)$

$B_0 = 2 \times 10^{-7}$

$k = 0.5 \times 10^3$

$\omega = 1.5 \times 10^{11}$

$\Rightarrow 2\pi f = 1.5 \times 10^{11}$

$\Rightarrow f = \dfrac{1.5 \times 10^{11}}{2 \times 3} = 0.25 \times 10^{11}$

$\Rightarrow f = 2.5 \times 10^{10}$ Hz Ans (b)

$\mu = \dfrac{c}{\lambda}$

$\Rightarrow \lambda = \dfrac{c}{\mu} = \dfrac{3 \times 10^8}{2.5 \times 10^{10}} = 1.2 \times 10^{-2}$ m Ans (a)

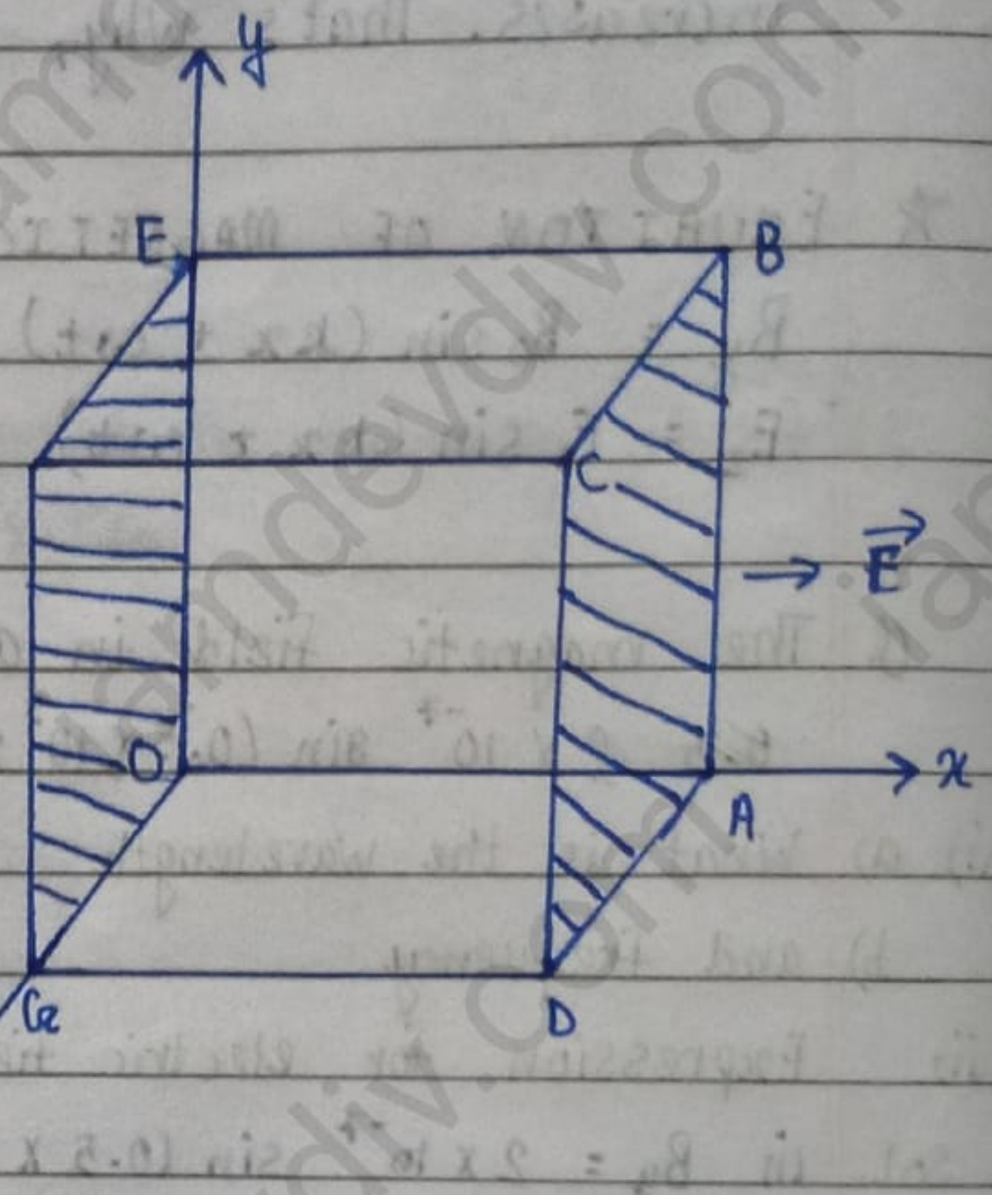
(ii) $C = \dfrac{E_0}{B_0}$

$\Rightarrow 3 \times 10^8 = \dfrac{E_0}{2 \times 10^{-7}}$

$\Rightarrow E_0 = 3 \times 10^8 \times 2 \times 10^{-7} = 60$ N/C Ans

★ EMWs ARE TRANSVERSE IN NATURE

Consider a plane electromagnetic wave is travelling in x-direction



In figure, a rectangular parallelo-pipe, does not enclose any charge

∴ Total electric flux across it must be zero

i.e. $\oint \vec{E} \cdot ds = 0$

$$\int_{ABCD} \vec{E} \cdot ds + \int_{GOEF} \vec{E} \cdot ds + \int_{GDAO} \vec{E} \cdot ds +$$

$$\int_{FCBE} \vec{E} \cdot ds + \int_{GFCD} \vec{E} \cdot ds + \int_{BAOE} \vec{E} \cdot ds = 0 \quad \text{---} \quad (1)$$

Since $\vec{E}$ does not depend upon y and z, $\vec{E}$ is considered along x-axis So the electric flux coming from the faces normal to y and z will be cancelled. Hence, eq^n (1) will reduce to

$$\int_{ABCD} \vec{E} \cdot ds + \int_{GOEF} \vec{E} \cdot ds = 0 \quad \text{---} \quad (2)$$

If E_x and E'_x are the values of electric field on faces ABCD and OGEF and S be the area of each face, then

$$\int_{ABCD} \vec{E} \cdot ds = E_x S$$

$$\int_{OGEF} \vec{E} \cdot ds = -E_x S$$

(2) $\Rightarrow E_x S - E'_x S = 0$

$S(E_x - E'_x) = 0$

$S \neq 0$

$E_x = E'_x$

This predicts that the field is static and static field can't propogate in the direction of wave propogation, so no component of $\vec{E}$ is parallel to the direction of wave propogation.

Hence, EMWs are transverse in nature which means they are propogating in y and z axis.