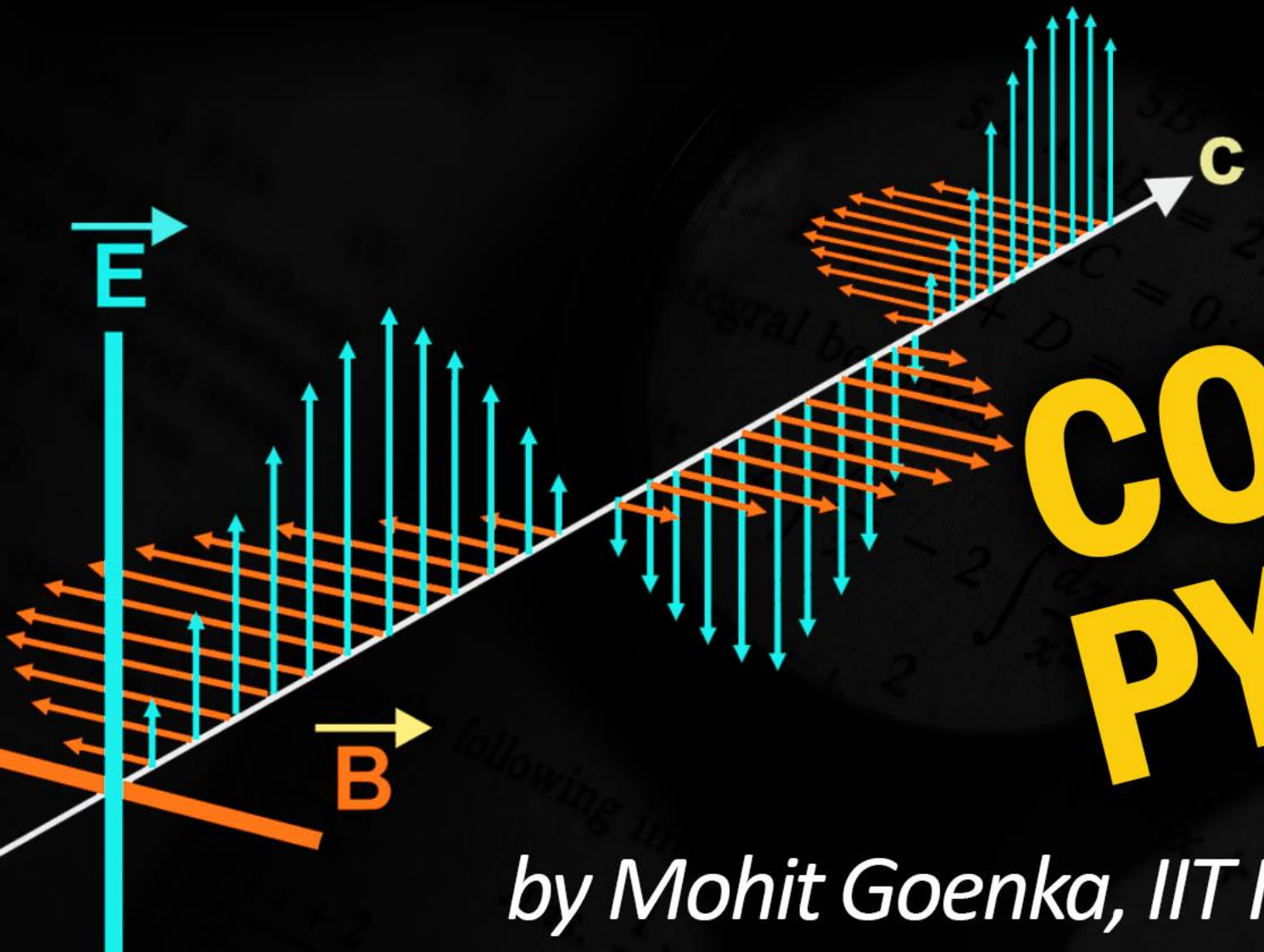
EM WAVES



JEE Main

CONCEPT PYQs

by Mohit Goenka, IIT Kharagpur

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TOPICS COVERED

1. Types of EM Waves
2. Displacement Current
3. Ampere – Maxwell Law
   a. NCERT Solved Ex.
4. Maxwell's Equation
5. EM Waves equation and Key Points
   a) Relation among c, E and B
   b) Intensity of EM Waves
   c) Speed of EM Waves
6. PYQs (Build your understanding)

1. TYPES OF EM WAVES

- Transverse waves
- Electric and magnetic field energy density is same.

$u_B = \frac{B^2}{2\mu_0}$, $u_E = \frac{1}{2}\epsilon_0 E^2$

Type	Wavelength Range	Production	Detection
Radio	>0.1 m	Rapid acceleration and deceleration of electrons in aerials	Receiver's aerials
Microwave	0.1 m to 1 mm	Klystron valve or magnetron valve	Point contact diodes
Infra-red	1 mm to 700 nm	Vibration of atoms and molecules	Thermopiles, Bolometer, Infrared photographic film
Light	700 nm to 400 nm	Electrons in atom emit light when they move from one energy level to a lower energy level	The eye, photocells, photographic film
Ultraviolet	400 nm to 1 nm	Inner shell electrons in atoms moving from one energy level to lower level	Photocells, Photographic film
X-rays	1 nm to 0.001 nm	X-ray tubes or inner shell electrons	Photographic film, Geiger tubes
Gamma rays	< 0.001 nm	Radioactive decay of the nucleus	Photographic film, Geiger tubes

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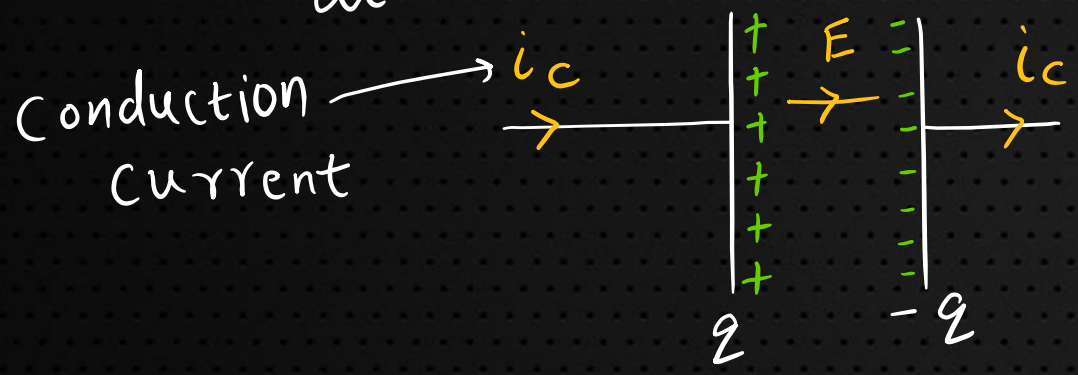
2. DISPLACEMENT CURRENT (i_d)

i_d is due to time varying electric field.

$$i_d = \varepsilon_0 \frac{d\phi_E}{dt}, \quad \phi_E \text{ is electric flux}$$



(a) If q changes, E changes

$$\Rightarrow i_d = \varepsilon_0 \frac{d(EA)}{dt}, \quad E = \frac{\sigma}{\varepsilon_0} = \frac{q}{A\varepsilon_0}$$

$$\Rightarrow i_d = \varepsilon_0 A \times \frac{1}{A\varepsilon_0}\frac{dq}{dt} = \frac{dq}{dt}$$

$\therefore$ In capacitor for time varying current conduction current is same as i_d.

(b) Between plates $i_d \neq 0$, $i_c = 0$

Outside plates $i_c \neq 0$, $i_d = 0$

(c) i_d is uniform across plate cross-section

3. AMPERE'S LAW

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

$$\longrightarrow i_c + \varepsilon_0 \frac{d\phi_E}{dt}$$

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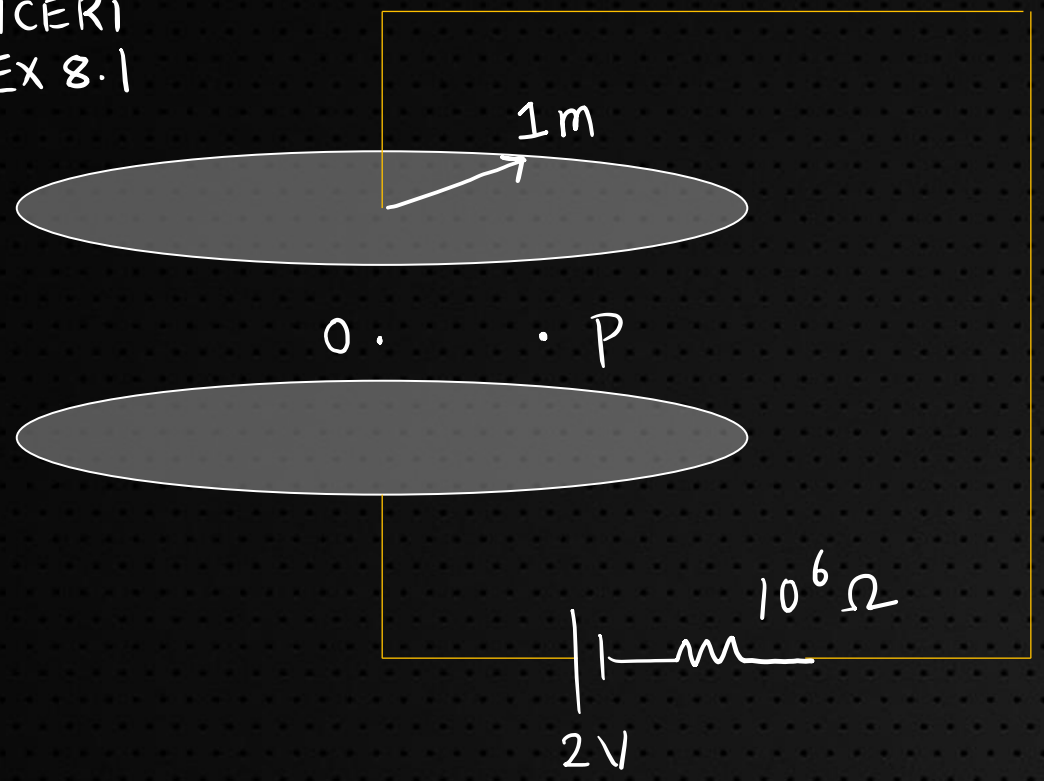
NCERT
Ex 8.1



$C = 10^{-9}$ F, at $t=0$ charging starts. Find B at P ($OP = 0.5$m) at $t = 10^{-3}$ s

Sol^n:

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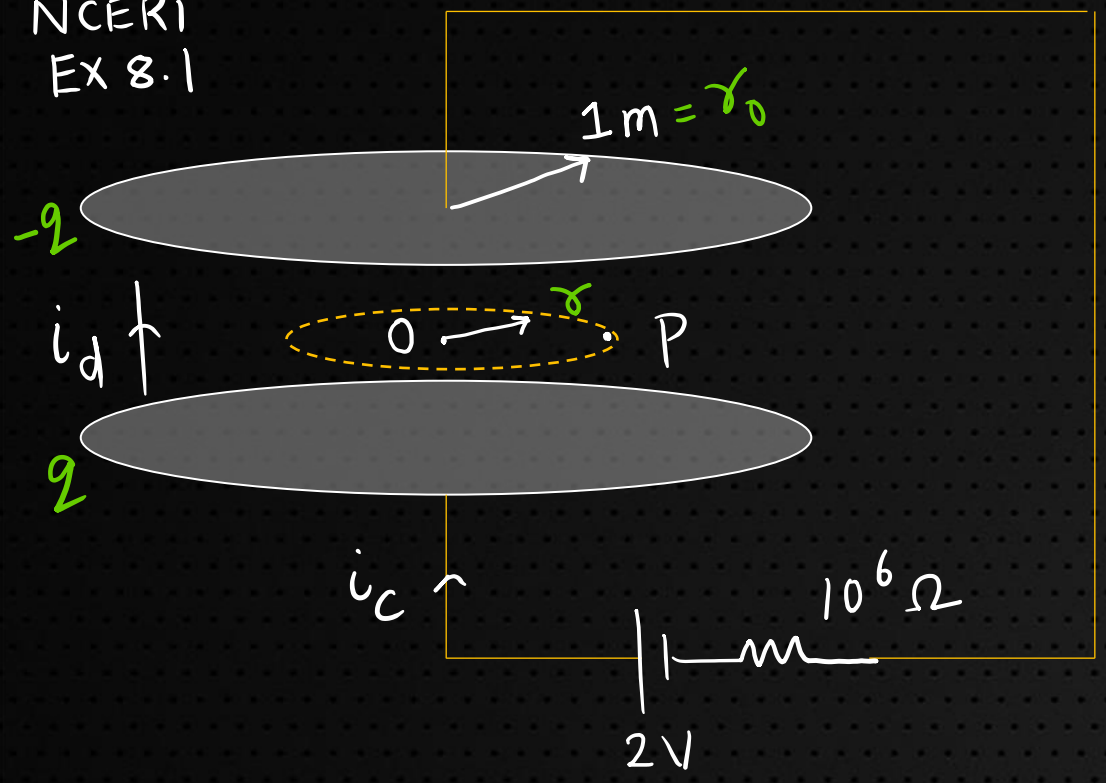
Ex 8.1



$C = 10^{-9}$ F, at t=0 charging starts. Find B at P (OP = 0.5m) at $t = 10^{-3}$ s

Sol^{n}: Consider Ampere loop of $\frac{1}{2}$m radius ($\to r$), parallel to plates.

$$\oint \bar{B}\cdot d\bar{l} = \mu_0 (i_c + i_d), \quad i_c = 0$$

$$\Rightarrow B \times 2\pi r = \mu_0 \varepsilon_0 \frac{d\phi_E}{dt}, \quad \phi_E = E\pi r^2$$

$$\Rightarrow \phi_E = \frac{\sigma}{\varepsilon_0}\pi r^2 = \frac{q}{\pi r_0^2 \varepsilon_0}\pi r^2$$

$$\boxed{\phi_E = q/4\varepsilon_0}$$

$$\Rightarrow B \times 2\pi r = \mu_0 \varepsilon_0 \times \frac{1}{4\varepsilon_0}\frac{dq}{dt}$$

$$\Rightarrow B \times \pi = \frac{\mu_0}{4}\frac{dq}{dt}, \quad 'q = q_0(1 - e^{-t/RC})'$$

$$\Rightarrow B\pi = \frac{\mu_0}{4} \times \frac{CV}{RC} e^{-t/RC}$$

$$\Rightarrow B = 10^{-7} \times \frac{2}{10^6} e^{-1} = \boxed{7.35 \times 10^{-14}\ T}$$

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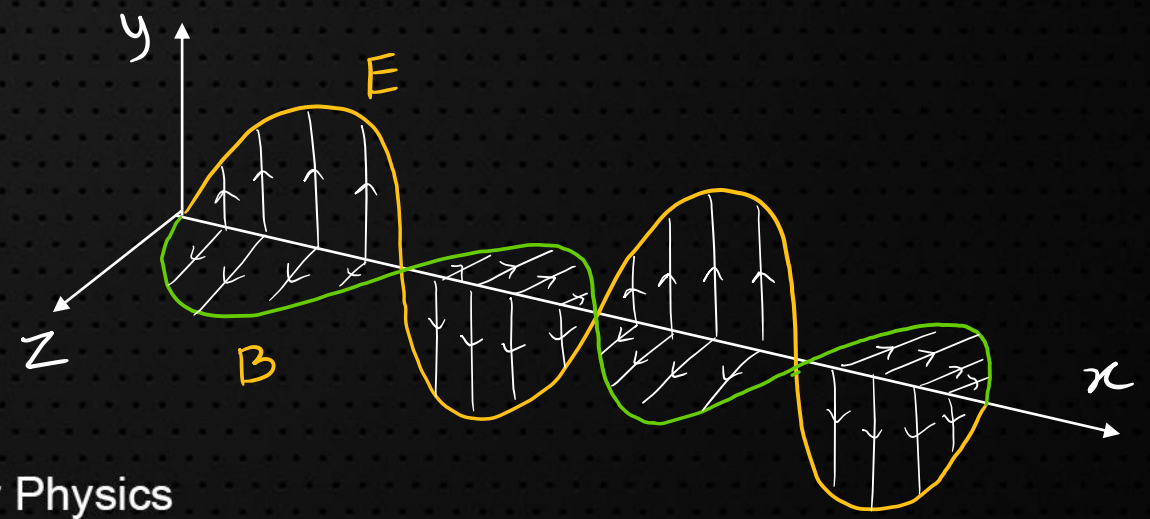
4. MAXWELL'S EQUATIONS

1. Gauss's Law in Electrostatics, $\Phi_E = \oint \bar{E} \cdot d\bar{A} = q_{in}/\varepsilon_0$
2. Gauss's Law for Magnetism, $\Phi_B = \oint \bar{B} \cdot d\bar{A} = 0$ { due to closed loop lines of field. This explains why monopole can't exist
3. Faraday's Law, $\oint \bar{E} \cdot d\bar{l} = -\frac{d\phi_B}{dt}$
4. Ampere-Maxwell Law, $\oint \bar{B} \cdot d\bar{l} = \mu_0 i_c + \mu_0 \varepsilon_0 \frac{d\phi_E}{dt}$

5. EM WAVES EQUATION AND KEY POINTS

$$\vec{E} = E_0 \sin(\omega t - kx)\,\hat{j}$$
$$\vec{B} = B_0 \sin(\omega t - kx)\,\hat{k}$$



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KEY POINTS

(a) RELATION AMONG $\hat{c}, \hat{E}, \hat{B}$ (unit vectors along direction of propagation, Electric field and magnetic field)

$$\hat{c} = \hat{E} \times \hat{B}, \quad \hat{B} = \hat{c} \times \hat{E}, \quad \hat{E} = \hat{B} \times \hat{c}$$

(b) FROM WAVE EQUATION

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

→ E along $\hat{j}$, $E_{rms} = E_0/\sqrt{2}$

→ WAVE propagation along +VE x-axis

(c) RELATION BETWEEN E_0 and B_0

$$E_0 = c B_0$$

(d) SPEED OF EM WAVES

$$c = \frac{1}{\sqrt{\mu_0 \varepsilon_0}} \text{ in free space}$$

$$c_{medium} = \frac{1}{\sqrt{\mu_r \mu_0 \varepsilon_r \varepsilon_0}} = \frac{c}{\sqrt{\mu_r \varepsilon_r}}$$

(e) INTENSITY

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

NOTE: In above intensity due to Electric field

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

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5 PYQs For UNDERSTANDING

1. AC voltage $V(t) = 20 \sin\omega t$ of frequency 50 Hz is applied to a parallel plate capacitor. The separation between the plates is 2 mm and the area is 1 m^2. The amplitude of the oscillating displacement current for the applied AC voltage is _____. [Take $\varepsilon_0 = 8.85 \times 10^{-12}$ F/m]

(1) 21.14 μA (2) 83.37 μA

(3) 27.79 μA (4) 55.58 μA

20th July Shift 1, JEE Main 2021

Solution on Next Page

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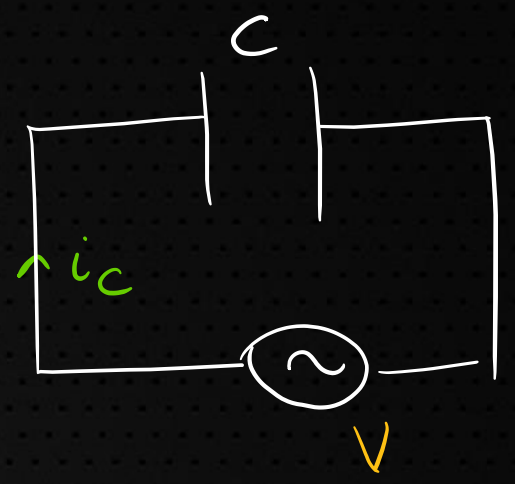
Sol^n:

$V = 20 \sin \omega t$

$\omega = 2\pi \times 50 = 100\pi$ rad/s

$C = A\varepsilon_0/d$



The amplitude of i_d is same as amplitude of i_c.

$$i_c = \frac{V_0}{X_C} = V_0 \omega C = V_0 \omega \frac{A\varepsilon_0}{d}$$

$$= \frac{20 \times 100\pi \times 1 \times 8.85 \times 10^{-12}}{2 \times 10^{-3}}$$

$$= 27.79\ \mu A$$

2. The magnetic field of a plane electromagnetic wave is given by $\vec{B} = B_0\hat{i}[\cos(kz-\omega t)] + B_1\hat{j}\cos(kz+\omega t)$ where, $B_0 = 3\times10^{-5}$ T and $B_1 = 2\times10^{-6}$ T. The rms value of the force experienced by a stationary charge $Q = 10^{-4}$ C at $z = 0$ is closest to

(a) 0.6 N (b) 0.1 N

(c) 0.9 N (d) 3×10^{-2} N

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Sol^{n}: As B_0 and B_1 are perpendicular to each other,

$B_{net} = \sqrt{B_0^2 + B_1^2} \approx 30\times10^{-6}$ T

$\therefore E_{net} = cB_{net} = 9\times10^3$ N/C

$E_{rms} = \frac{E_{net}}{\sqrt{2}} = \frac{9}{\sqrt{2}}\times10^3$ N/C

$\therefore F_{rms} = QE_{rms}$

$= 10^{-4}\times\frac{9}{\sqrt{2}}\times10^3 \approx 0.6$ N

3. An electromagnetic wave is represented by the electric field $\vec{E} = E_0\hat{n}\sin[\omega t + (6y - 8z)]$. Taking unit vectors in x, y and z directions to be $\hat{i}, \hat{j}, \hat{k}$, the direction of propogation $\hat{s}$, is

(a) $\hat{s} = \dfrac{3\hat{i} - 4\hat{j}}{5}$

(b) $\hat{s} = \dfrac{-4\hat{k} + 3\hat{j}}{5}$

(c) $\hat{s} = \left(\dfrac{-3\hat{j} + 4\hat{k}}{5}\right)$

(d) $\hat{s} = \dfrac{4\hat{j} - 3\hat{k}}{5}$

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Sol^{n}:

$$\vec{E} = E_0\hat{n}\sin[\omega t - (-6y + 8z)]$$

$$\therefore \hat{s} = \frac{-6\hat{j} + 8\hat{k}}{\sqrt{6^2 + 8^2}} = \frac{-6\hat{j} + 8\hat{k}}{10}$$

$$= \frac{-3\hat{j} + 4\hat{k}}{5}$$

4. A 27 mW laser beam has a cross – sectional area of 10 mm^2. The magnitude of the maximum electric field in this electromagnetic wave is given by

(a) 2 kV/m (b) 0.7 kV/m

(c) 1kV/m (d) 1.4 kV/m

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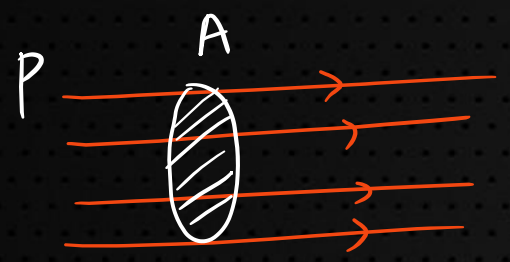

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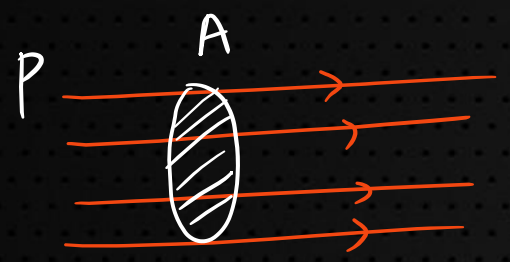

Sol^n:

$$I = \frac{1}{2}\epsilon_0 c E_0^2$$

$$\Rightarrow E_0 = \sqrt{\frac{2I}{\epsilon_0 c}}, \quad I = \frac{P}{A}$$

$$= \sqrt{\frac{2P}{\epsilon_0 c A}}$$

$$= \sqrt{\frac{2 \times 27 \times 10^{-3}}{8.85 \times 10^{-12} \times 3 \times 10^8 \times 10 \times 10^{-6}}}$$

$$\approx 1.4 \text{ kV/m}$$

5. For a plane electromagnetic wave, the magnetic field at a point x and time t is

$$\vec{B}(x,t) = [1.2\times10^{-7}\sin(0.5\times10^{3}x + 1.5\times10^{11}t)\hat{k}]\,\mathrm{T}$$

The instantaneous electric field $\vec{E}$ corresponding to $\vec{B}$ is (speed of light $c = 3\times10^{8}\ \mathrm{ms^{-1}}$)

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(a) $\vec{E}(x,t) = [36\sin(0.5\times10^{3}x + 1.5\times10^{11}t)\hat{k}]\dfrac{\mathrm{V}}{\mathrm{m}}$

(b) $\vec{E}(x,t) = [-36\sin(0.5\times10^{3}x + 1.5\times10^{11}t)\hat{j}]\dfrac{\mathrm{V}}{\mathrm{m}}$

(c) $\vec{E}(x,t) = [36\sin(1\times10^{3}x + 0.5\times10^{11}t)\hat{j}]\dfrac{\mathrm{V}}{\mathrm{m}}$

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Sol^n: From eq^n, $\hat{c} = -\hat{i}$, $\hat{B} = \hat{k}$

$\therefore \hat{E} = \hat{B} \times \hat{c} = \hat{k} \times (-\hat{i}) = \boxed{-\hat{j}}$

$E_0 = cB_0 = 3 \times 10^8 \times 1.2 \times 10^{-7} = \boxed{36\ V/m}$

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