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ELECTRODYNAMICS

E.M. Waves

$\vec{\nabla} \cdot \vec{E} = \frac{\rho}{\varepsilon_0}$ (Gauss's law)

$\vec{\nabla} \cdot \vec{B} = 0$

$\vec{\nabla} \times \vec{E} = \frac{-\partial B}{\partial t}$ (Faraday's law)

$\vec{\nabla} \times \vec{B} = \mu_0 \vec{J}$ (Ampere's law)

$$\vec{\nabla} = \hat{i}\frac{\partial}{\partial x} + \hat{j}\frac{\partial}{\partial y} + \hat{k}\frac{\partial}{\partial z}$$

Suppose $\vec{A} = A_x\hat{i} + A_y\hat{j} + A_z\hat{k}$

$\vec{\nabla} \cdot \vec{A}$ = divergence of A

$$\vec{\nabla} \cdot \vec{A} = \frac{\partial A_x}{\partial x} + \frac{\partial A_y}{\partial y} + \frac{\partial A_z}{\partial z}$$ (scalar qty)

$\vec{\nabla} \times \vec{A}$ = Curl of A

$$\bar{\nabla} \times \bar{A} = \begin{vmatrix} \hat{i} & \hat{j} & \hat{k} \\ \partial/\partial x & \partial/\partial y & \partial/\partial z \\ A_x & A_y & A_z \end{vmatrix}$$

Grad of ϕ

$$\nabla\phi = \frac{\partial\phi}{\partial x}\hat{i} + \frac{\partial\phi}{\partial y}\hat{j} + \frac{\partial\phi}{\partial z}\hat{k}$$

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div (curl) = 0

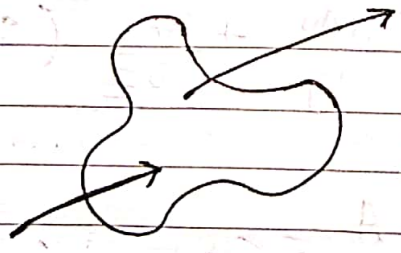
$$\vec{\nabla}\cdot(\vec{\nabla}\times\vec{B}) = 0$$

$$\int_V \vec{\nabla}\cdot\vec{A}\,dV = \oint_S \vec{A}\,ds \quad \text{(Gauss Theorem)}$$

$$\int_S (\vec{\nabla}\times\vec{A})\cdot ds = \oint_l \vec{A}\cdot dl \quad \text{(Stoke Theorem)}$$

Take div both side in eq^n 4

$$\underbrace{\vec{\nabla}\cdot(\vec{\nabla}\times\vec{B})}_{0 \text{ (always)}} = \mu_0 \underbrace{(\vec{\nabla}\cdot\vec{J})}_{0 \text{ if } J \text{ is constant.}}$$



I (going Inside) = I (going outside)

$$\frac{dq}{dt} = -\oint_S J\cdot ds$$

$$\frac{\partial}{\partial t}\left[\int_V \rho\,dv\right] = -\oint J\cdot ds$$

$$\int_V \frac{\partial \rho}{dt}\,dv = -\int \vec{\nabla}\cdot\vec{J}\,dV \quad \text{(Gauss Theorem)}$$

$$= \int \left(\frac{\partial \rho}{\partial t} + \vec{\nabla}\cdot\vec{J}\right) dv = 0.$$

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Use eq^n (1) (Gauss Law)

$$\frac{\partial}{\partial t}(\varepsilon_0 \nabla \cdot E) + \vec{\nabla} \cdot \vec{J} = 0$$

$$\nabla \cdot \left(\varepsilon_0 \frac{\partial \vec{E}}{\partial t} + \vec{J} \right) = 0$$

↳ Displacement Current

After maxwell's Modification

$$\nabla \cdot \bar{E} = \rho / \varepsilon_0$$

$$\nabla \cdot \bar{B} = 0$$

$$\bar{\nabla} \times \bar{E} = -\frac{\partial B}{\partial t}$$

$$\nabla \times \bar{B} = \mu_0 \left[\vec{J} + \varepsilon_0 \frac{\partial E}{\partial t} \right]$$

⇒ Maxwells equation in free Space:-

$(\rho = 0, \quad \sigma = 0 \Rightarrow J = \sigma E = 0)$

$$\nabla \cdot \bar{E} = 0$$

$$\bar{\nabla} \cdot \bar{B} = 0$$

$$\nabla \times \bar{E} = -\frac{\partial B}{\partial t}$$

$$\nabla \times \bar{B} = \mu_0 \varepsilon_0 \frac{\partial E}{\partial t}.$$

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⇒ Conducting Medium

$\rho_f \qquad J \neq 0$

$$\nabla \cdot \vec{E} = \frac{\rho_f}{\varepsilon}$$

$$\nabla \cdot \bar{B} = 0$$

$$\nabla \times \bar{E} = -\frac{\partial \bar{B}}{\partial t}$$

$$\nabla \times \bar{B} = \mu\left[\bar{J} + \varepsilon \frac{\partial \bar{E}}{\partial t}\right]$$

⇒ Dielectric Medium:-

$J = 0 \qquad \rho = 0$

$\varepsilon_0 \to \varepsilon, \quad \mu_0 \to \mu$

$$\nabla \cdot \bar{E} = 0$$

$$\nabla \cdot \bar{B} = 0$$

$$\nabla \times \bar{E} = -\frac{\partial B}{\partial t}$$

$$\nabla \times \bar{B} = \mu\varepsilon \frac{\partial \bar{E}}{\partial t}$$

* Maxwell's Eq^n for Some Medium

$$\nabla \cdot \bar{E} = \rho / \varepsilon \quad \text{—— (1)}$$

$$\nabla \cdot \bar{B} = 0 \quad \text{—— (2)}$$

$$\nabla \times \bar{E} = -\partial B / \partial t \quad \text{—— (3)}$$

$$\nabla \times \bar{B} = \mu J + \mu\varepsilon \frac{\partial E}{\partial t}$$

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Take curl of Eq^n (3) Both side

$$\nabla \times (\nabla \times \bar{E}) = -\frac{\partial}{\partial t}(\nabla \times \bar{B})$$ from eq^n (3.)

$$\nabla(\nabla \cdot \bar{E}) - \nabla^2 \bar{E} = -\frac{\partial}{\partial t}\left(\mu J + \mu \varepsilon \frac{\partial \bar{E}}{\partial t}\right)$$

$$0 - \nabla^2 \bar{E} = -\frac{\partial}{\partial t}\left(\mu \sigma \bar{E} + \mu \varepsilon \frac{\partial E}{\partial t}\right)$$

$$-\nabla^2 \bar{E} = -\mu \sigma \frac{\partial E}{\partial t} - \mu \varepsilon \frac{\partial^2 E}{\partial t^2}$$

$$-\nabla^2 \bar{E} + \mu \sigma \frac{\partial E}{\partial t} + \mu \varepsilon \frac{\partial^2 E}{\partial t^2} = 0$$

Curl of Eq^n (4) Both side

$$\nabla \times (\nabla \times \bar{B}) = \nabla \times \bar{J}_M + \mu \varepsilon \frac{\partial}{\partial t}(\nabla \times \bar{E})$$

$$-\nabla^2 \vec{B} = (\nabla \times \vec{J})\mu + \mu \varepsilon \frac{\partial}{\partial t}\left(-\frac{\partial \vec{B}}{\partial t}\right)$$

$$-\nabla^2 \vec{B} = (\nabla \times \vec{E})\sigma \mu + \mu \varepsilon \left(\frac{-\partial^2 \vec{B}}{\partial t^2}\right)$$

$$-\nabla^2 \vec{B} = -\mu \sigma \frac{\partial \vec{B}}{\partial t} - \mu \varepsilon \frac{\partial^2 \bar{B}}{\partial t^2}$$

$$-\nabla^2 \vec{B} + \mu \sigma \frac{\partial \vec{B}}{\partial t} + \mu \varepsilon \frac{\partial^2 \vec{B}}{\partial t^2}$$

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(ELECTRODYNAMICS)

Maxwell's Equation

$$\vec{\nabla}\cdot\vec{E} = \frac{\rho}{\varepsilon_0} \quad \text{——— (1)}$$

$$\vec{\nabla}\cdot\vec{B} = 0 \quad \text{——— (2)}$$

$$\vec{\nabla}\times\vec{E} = \frac{-\partial\vec{B}}{\partial t} \quad \text{——— (3)}$$

$$\vec{\nabla}\times\vec{B} = \mu_0\vec{J} + \mu_0\varepsilon_0\frac{\partial\vec{E}}{\partial t} \quad \text{——— (4)}$$

Wave propagation (Energy)

How energy is transfered by E.M. wave.

$$W_e = \int_{\tau} \frac{\varepsilon_0}{2} E^2 d\tau$$

$\tau \rightarrow$ volume element

The work necessary to assemble a static charge against coloumb's repulsion in the electrostatic energy W_e

$$W_m = \int_{\tau} \frac{1}{2\mu_0} B^2 d\tau$$

Work required to get currents going against the back emf in magnetic energy W_m

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Total Energy stored in electromagnetic field is U_{em}

$$U_{em} = \int_\tau \frac{\varepsilon_0}{2} E^2 dt + \int_\tau \frac{1}{2\mu_0} B^2 dt$$

$$U_{em} = \frac{1}{2} \int_\tau \left(E^2 \varepsilon_0 + B^2 \frac{1}{\mu_0} \right) d\tau$$

Suppose we have charges and current configurations at time 't' which produces Field E & B after an instant 'dt' charges are moved a little bit, how much work is done by E.M. forces acting on these charges in the interval 'dt'.

Lorentz force

$$dW = \vec{F} \cdot \vec{dl}$$

$$= q(\vec{E} + \vec{v} \times \vec{B}) \cdot \vec{dl}$$

$$\vec{dl} = \vec{v} dt$$

$$dW = q(\vec{E} + \vec{v} \times \vec{B}) \cdot \vec{v} dt$$

$$= q\vec{E} \cdot \vec{v} dt$$

$$\frac{dW}{dt} = q\vec{E} \cdot \vec{v}$$

$\tau \rightarrow$ Volume Element

$$\frac{dW}{dt} = \int_\tau \vec{E} \cdot \vec{v} \rho d\tau$$

$$\vec{J} = \rho \vec{v}$$

$$\frac{dW}{dt} = \int_\tau \vec{E} \cdot \vec{J} d\tau \quad \text{——— (5)}$$

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$\vec{E}\cdot\vec{J} = ?$ Work per unit time per unit volume.
W/t/vol

Using Eq^n (4) Eliminate $\vec{J}$ in eq^n (5)

$$\vec{J} = \frac{\vec{\nabla}\times\vec{B}}{\mu_0} - \frac{\cancel{\mu_0}\,\varepsilon_0}{\cancel{\mu_0}}\frac{\partial\vec{E}}{\partial t}$$

$$= \frac{\vec{\nabla}\times\vec{B}}{\mu_0} - \varepsilon_0\frac{\partial\vec{E}}{\partial t}$$

$$\vec{E}\cdot\vec{J} = \vec{E}\cdot\left(\frac{1}{\mu_0}(\vec{\nabla}\times\vec{B}) - \varepsilon_0\frac{\partial\vec{E}}{\partial t}\right)$$

$=$

using

$$\vec{\nabla}\cdot(\vec{E}\times\vec{B}) = \vec{B}\cdot(\vec{\nabla}\times\vec{E}) - \vec{E}\cdot(\vec{\nabla}\times\vec{B})$$

$$\vec{E}\cdot(\vec{\nabla}\times\vec{B}) = \vec{B}\cdot(\vec{\nabla}\times\vec{E}) - \vec{\nabla}\cdot(\vec{E}\times\vec{B})$$

$$\vec{E}\cdot\vec{J} = \frac{1}{\mu_0}\left\{\vec{B}\cdot(\vec{\nabla}\times\vec{E}) - \vec{\nabla}\cdot(\vec{E}\times\vec{B}) - \varepsilon_0\vec{E}\cdot\frac{\partial\vec{E}}{\partial t}\right\}$$

using Maxwell eq^n (3)

$$\vec{E}\cdot\vec{J} = \frac{1}{\mu_0}\left[\vec{B}\cdot\left(-\frac{\partial\vec{B}}{\partial t}\right) - \vec{\nabla}\cdot(\vec{E}\times\vec{B})\right\} - \varepsilon_0\vec{E}\frac{\partial\vec{E}}{\partial t}$$

$$\frac{dw}{dt} = \int_\tau \frac{1}{\mu_0}\left(\vec{B}\cdot\left(-\frac{\partial\vec{B}}{\partial t}\right)\right) - \varepsilon_0\vec{E}\cdot\frac{\partial\vec{E}}{\partial t} - \frac{1}{\mu_0}\nabla\cdot(\vec{E}\times\vec{B})$$

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$$U_{em} = \frac{1}{2}\int_\tau \left(\varepsilon_0 E^2 + \frac{1}{\mu_0} B^2\right) d\tau$$

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$$\frac{dw}{dt} = \int \frac{-1}{\mu_0} \vec{B_0}\left(\frac{\partial \vec{B}}{\partial t}\right) - \varepsilon_0 \vec{E}\cdot\frac{\partial \vec{E}}{\partial t} - \frac{1}{\mu_0}\vec{\nabla}\cdot(\vec{E}\times\vec{B})\, d\tau$$

$$\Downarrow \qquad\qquad \Downarrow$$

$$\frac{1}{2}\frac{d}{dt}(B^2) - \frac{1}{2}\frac{d}{dt}(E^2)$$

$$\cancel{\frac{dw}{dt} = \int_\tau \left[\frac{-1}{2\mu_0} B^2 + \frac{\varepsilon_0}{2} E^2\right.}$$

$$\frac{dw}{dt} = \int_\tau \left[-\frac{1}{2\mu_0}\frac{dB^2}{dt} - \varepsilon_0 \frac{dE^2}{dt}\right] d\tau - \int_\tau \nabla\cdot(\vec{E}\times\vec{B})\, d\tau$$

$$\frac{dw}{dt} = -\frac{d}{dt}\left[\int_\tau \frac{1}{2\mu_0} B^2 + \frac{\varepsilon_0}{2} E^2\, d\tau\right] - \int_\tau \frac{1}{\mu_0}\nabla\cdot(\vec{E}\times\vec{B})\, d\tau$$

$$\frac{dw}{dt} = -\frac{d}{dt} U_{em} - \int_\tau \frac{1}{\mu_0}\nabla\cdot(\vec{E}\times\vec{B})\, d\tau$$

Using Gauss divergence theorem

$$\frac{dw}{dt} = -\frac{d}{dt} U_{em} - \oint_S \frac{1}{\mu_0}(\vec{E}\times\vec{B})\, d\vec{a}$$

S = surface enclosing the volume τ

Poynting Theorem:

$$\frac{dw}{dt} = -\frac{d}{dt} U_{em} - \oint_S \frac{1}{\mu_0}(\vec{E}\times\vec{B})\, d\vec{a}$$

U_{em} → Total Energy stored in field.

$\oint_S \frac{1}{\mu_0}(\vec{E}\times\vec{B})\, d\vec{a}$ → rate at which energy is carried out of the volume τ across the boundary surface S.

$d\tau$

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$$\frac{1}{\mu_0}(\vec{E}\times\vec{B}) = \vec{S} \longrightarrow \text{energy}/A/t$$

power/A

poynting vector

Energy flux density

poynting theorem

$$\frac{dw}{dt} = -\frac{d}{dt}U_{em} - \oint_S \vec{S}\cdot d\vec{a}$$

The work done on the charges by E.M. field is equal to the decr in energy stored in field less the energy that flowed out to the surface. The energy per unit time, per unit area transported by the field is called poynting vector.

physical Significance of poynting vector:-

In an EM field, the flow of energy is given by poynting vector. For an EM wave this vector is in the direction of propagation and account for radiation pressure. However in the static electromagnetic field the poynting vector can of course be non-zero

EM WAVE EQUATION (General)

$$\nabla^2 \vec{E} - \mu\sigma \frac{\partial \bar{E}}{\partial t} - \mu\varepsilon \frac{\partial^2 \bar{E}}{\partial t^2} = 0$$

$$\nabla^2 \vec{B} - \mu\sigma \frac{d\bar{B}}{\partial t} - \mu\varepsilon \frac{\partial^2 B}{\partial t^2} = 0$$

Free Space / Vacuum

$\sigma = 0$, $\mu \Rightarrow \mu_0$
$\varepsilon \Rightarrow \varepsilon_0$

σ = Surface charge density

$$\left.\begin{aligned} \nabla^2 E - \mu_0 \varepsilon_0 \frac{\partial^2 E}{\partial t^2} &= 0 \\ \nabla^2 B - \mu_0 \varepsilon_0 \frac{\partial^2 B}{\partial t^2} &= 0 \end{aligned}\right\} \text{①}$$

$$\nabla^2 A - \frac{1}{v^2} \frac{\partial^2 A}{\partial t^2} = 0 \Big\} \text{ classical wave equation} \quad \text{②}$$

Comparing eq^n ① with ②

$$v = \frac{1}{\sqrt{\mu_0 \varepsilon_0}} = 3 \times 10^8 \, m/sec$$

⇒ Empty space support the propagation of E.M. waves with speed 3×10^8 m/sec = speed of light.

Hence light is an E.M. wave

$$\bar{E}(r,t) = E_0 e^{i(\bar{k}\cdot\bar{r} - \omega t)} \hat{n} \longrightarrow \text{Polarization Vector.}$$

$$\bar{B}(r,t) = B_0 e^{i(\bar{k}\cdot\bar{r} - \omega t)} (\hat{k} \times \hat{n})$$

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propagation wave vector $\vec{k}$

$$\vec{k} = \frac{2\pi}{\lambda}\hat{k} = \frac{2\pi\nu}{c}\hat{k} = \frac{\omega}{c}\hat{k}$$

$$\vec{k} = k_x\hat{i} + k_y\hat{j} + k_z\hat{k}$$

$$E_0 = E_{0x}\hat{i} + E_{0y}\hat{j} + E_{0z}\hat{k}$$

$$\vec{r} = x\hat{i} + y\hat{j} + z\hat{k}$$

as

$\vec{\nabla}\cdot\vec{E} = 0$

$\vec{\nabla}\cdot\left(E_0 e^{i(\vec{k}\cdot\vec{r}-\omega t)}\right)$

$\downarrow$

$\vec{k}\cdot\vec{E} = 0$ ——— (3)

$\downarrow$ $\vec{k} \perp \vec{E}$

$\vec{\nabla}\cdot B = 0$

$\vec{\nabla}\cdot\left(B_0 e^{i(\vec{k}\cdot\vec{r}-\omega t)}\right)$

$\downarrow$

$\vec{k}\cdot\vec{B} = 0$ ——— (4)

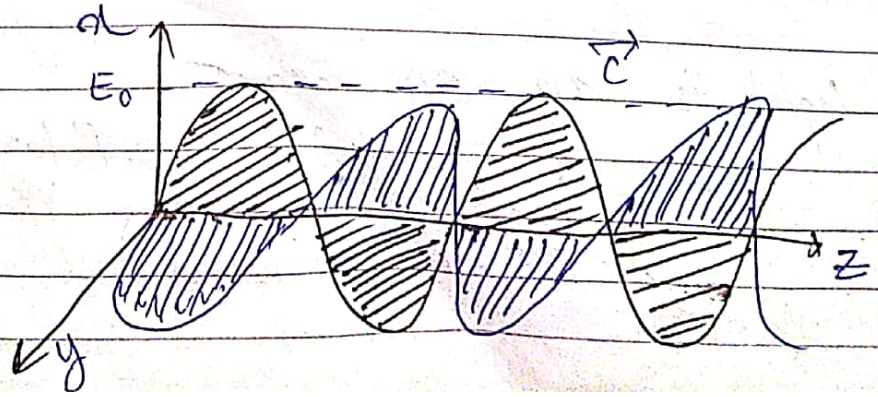
$B = \mu_0 H$

$\Rightarrow \vec{k}\cdot\vec{H} = 0$

$\vec{k} \perp \vec{B}$ or $\vec{k} \perp \vec{H}$

$\Rightarrow$ $\vec{E}$ & $\vec{H}$ (or $\vec{B}$) are perpendicular to $\vec{k}$

$\Rightarrow$ E.M. waves are transverse in Nature in free Space.



$\vec{E}(z,t) = E_0 e^{i(kz-\omega t)}\hat{x}$

$\vec{B}(z,t) = B_0 e^{i(kz-\omega t)}\hat{y}$

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Also

$$\vec{\nabla} \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$ (proof is not important)

$$\cancel{i}\,\vec{k} \times \vec{E} = \cancel{i}\,\omega \vec{B}$$

$$\vec{B} = \frac{\vec{k} \times \vec{E}}{\omega} = \frac{\omega/c\,\hat{k} \times \vec{E}}{\omega} = \frac{\hat{k} \times \vec{E}}{c}$$

$$H = \frac{\hat{k} \times E}{\mu_0 c}$$

$$\vec{B} = \frac{\vec{k} \times \vec{E}}{c}, \quad E$$

$\vec{E}$ & $\vec{B}$ are in phase & ~~Mutu~~ Mutually $\perp$

Real Amplitudes $B_0 = \frac{k}{\omega} E_0 = \frac{E_0}{c}$

$$B(r,t) = \frac{E_0}{c} e^{i(kr - \omega t)}$$

$$\hat{k} \times \hat{n} = \frac{1}{c}(\vec{k} \times \vec{E})$$

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

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

$$\frac{E_0}{H_0} = \mu_0 c = \frac{\mu_0}{\sqrt{\mu_0 \varepsilon_0}} = \sqrt{\frac{\mu_0}{\varepsilon_0}} = 376.6\,\Omega = Z$$

Impedance of free space.

$$\vec{S} = \frac{\vec{E} \times \vec{B}}{\mu_0} = \vec{E} \times \vec{H}$$

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Problems

Q→1 In free space $\vec{E}(z,t) = 10^3 \sin(\omega t - \beta z)\hat{a}_y$ obtain $\vec{H}(z,t)$?

$$\vec{S} = \vec{E} \times \vec{H}$$
$$\downarrow \quad \downarrow \quad \downarrow$$
$$\hat{z} \quad \hat{y} \quad ? = (-\hat{x})$$

$$\vec{H}(z,t) = \left(\frac{E_0}{\mu_0 c}\right) \sin(\omega t - \beta z)$$

$$= 2.65 \sin(\omega t - \beta z)\,(-\hat{x})$$

Ans

Q.-2 For a plane EM wave

$$E_z = a \cos \omega x \cos \omega c t$$
$$H_y = -a \sin \omega x \sin \omega c t$$

find instantaneous value of poynting vector

$$S = \bar{E} \times \bar{H}$$
$$= -\frac{1}{4} a^2 \sin 2\omega x \sin 2\omega c t \quad \text{(Ans)}$$

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Q. 3. Earth receives 2 cal/min/cm^2 of solar energy. what are amplitude of E. field & mag. field.

V/m

$$S = 2\,cal\ cal/min/cm^2$$
$$= 2 \times 4.2\ J/min/cm^2$$
$$= \frac{2 \times 4.2}{60}\ J/sec/cm^2$$
$$= \frac{2 \times 4.2}{60} \times 10^4\ J/sec/m^2$$
$$S = 1400\ J/sec/m^2$$

$\vec{S} = \vec{E} \times \vec{H}$

$E \perp H$

$= EH \sin 90$

$S = EH$

$S = EH$

$EH = 1400$ —— (1)

$\frac{E}{H} = 377$ —— (2)

$E = 726.2$ V/m

$H = 1.98$ A/m

Maxwell equation in dielatric Medium

$J = 0 \qquad \rho = 0 \qquad \varepsilon_0 \to \varepsilon \qquad \mu_0 \to \mu$

$$\nabla \cdot E = 0$$
$$\nabla \cdot B = 0$$
$$\nabla \times E = -\frac{\partial B}{\partial t}$$
$$\nabla \times B = \mu\varepsilon \frac{\partial E}{\partial t}$$

$$\nabla^2 E - \mu_0 \frac{\partial E}{\partial t} - \mu\varepsilon \frac{\partial^2 E}{\partial t^2} = 0$$

$$\nabla^2 B - \mu_0 \frac{\partial B}{\partial t} - \mu\varepsilon \frac{\partial^2 B}{\partial t^2} = 0$$

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Linear dielectric Medium

$$\nabla^2 E - \mu \varepsilon \frac{\partial^2 E}{\partial t^2} = 0$$

$$\nabla^2 B - \mu \varepsilon \frac{\partial^2 B}{\partial t^2} = 0$$

$$V = \frac{1}{\sqrt{\mu \varepsilon}} < C = 3 \times 10^8 \, m/sec$$

$$\varepsilon = \varepsilon_r \varepsilon_0$$
$$\mu = \mu_r \mu_0$$

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

Refractive Index, $n = \frac{C}{V} = \sqrt{\mu_r \varepsilon_r}$

Q-4 Assuming that all the energy from a 1000 Watt lamp is radiated uniformly calculate the avg. values of Electric f. & Mag. field. at a distance of 2m from the lamp.

$S \rightarrow$ Power / Area

$$S = \frac{1000}{4\pi(4)} = EH$$

$$\frac{E}{H} = 377$$

$E = 86.59$
$H = 0.23$

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