PHYSICS INDUCTION
An institute of Science & Mathematics

Vinita Chawla
M.Sc. Physics (HRC, Delhi University)
M.Sc. Computer Science, B.Ed.,
CTET, HTET, PSTET, CSB Qualified
Contact: 91-8168258349
physicsinduction@gmail.com

CLASS XII : NOTES : CHAPTER–8 : ELECTROMAGNETIC WAVES : PHY

- q at rest : $\vec{E}$, q moving with const velocity : $\vec{B}$, Accelerated q : EM field
- A changing $\vec{E}$ → produces $\vec{B}$, A changing $\vec{B}$ – produces $\vec{E}$,
- $\vec{E}$ & $\vec{B}$ are inter-related & eq^n describing them are identical & symmetrical
- $E = E_0 \sin\omega(t - x/c)$: E – sinusoidally varying $\vec{E}$ at pos^n x at time, t. E is in Y–Z plane, ⊥r to the direct^n of propagation.
- $B = B_0 \sin\omega(t - x/c)$: B – sinusoidally varying $\vec{B}$ associated with $\vec{E}$. This $\vec{B}$ is ⊥r to the direct^n of propagation as well as to $\vec{E}$.

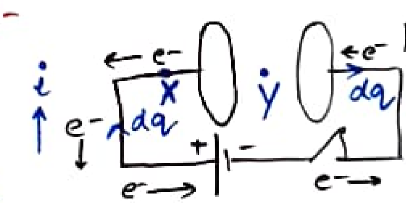
Such a comb^n of mutually ⊥r $\vec{E}$ & $\vec{B}$ is referred to as an EM wave in vacuum.

- **Maxwell** (1831 – 1879) : introduced the concept of displacement current & build classical EM theory.
- Hertz (1887): produced and detected EM waves
- Dr Jagdish Chandra Bose (1895): produced & observed EM waves of shorter λ(≃10mm)
- Guglielmo Marconi (1901): transmitted EM waves across Eng channel & across Atlantic ocean.
- EM waves transport momentum & energy & also exert pressure.

CHANGING ELECTRIC FIELD PRODUCES MAGNETIC FIELD

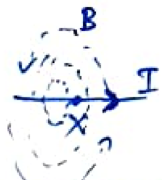
Maxwell's Expt to prove this point :-

Consider a parallel plate capacitor being charged by a battery



$$i = \frac{dq}{dt}$$

At pt X :



mag. field will be produced

$\oint \vec{B} \cdot d\vec{l} = \mu_0 i$ (Ampere's circuital Law)

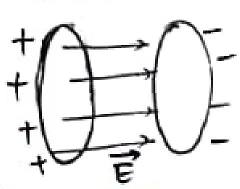
At pt Y (b/w the plates of capacitor) (vacuum/free space) : $\oint \vec{B} \cdot d\vec{l} = \mu_0 (0)$ [Ampere's circuital law]

no i ⇒ no $\vec{B}$

⇒ $B = 0$

But, Maxwell placed a compass needle at pt Y & needle deflected

As charge is flowing from one plate of the capacitor to another. With time one plate of the capacitor b'comes more & more positively charged & other plate of the capacitor b'comes more & more negatively charged ∴ $\vec{E}$ b/w the plates will gradually increase ⇒ changing $\vec{E}$, produces $\vec{B}$



⇒ Ampere's Circuital law is inconsistent.

Idea of Displacement Current :- produced by Changing $\vec{E}$. (or changing ϕ_E), i_d also explains continuity of current in capacitors.

i_c: Conduction Current
i_d: Displacement Current

$$i_c = \frac{dq}{dt}$$

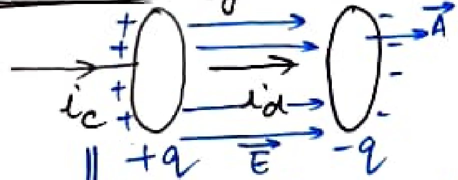
$$\& \quad i_d = \varepsilon_0 \frac{d\phi_E}{dt}$$

∴ Resultant magnetic field is given by:

$$\oint \vec{B}\cdot d\vec{l} = \mu_0 i_c + \mu_0 i_d$$

$$= \mu_0 [i_c + i_d] = \mu_0 \left[i_c + \varepsilon_0 \frac{d\phi_E}{dt}\right]$$ ← Modified Ampere's law / Ampere-Maxwell Law

i_d across an area in the region b/w the plates & parallel to it is equal to the conduction current in the connecting wires : (i_c)



T.P. : $i_c = i_d$

$$i_c = \frac{dq}{dt}$$

$\phi_E = \vec{E}\cdot\vec{A} = EA\cos 0^\circ = EA$

$\& \; E = \frac{\sigma}{2\varepsilon_0} + \frac{\sigma}{2\varepsilon_0} = \frac{\sigma}{\varepsilon_0} = \frac{q}{A\varepsilon_0}$

$$\& \quad i_d = \varepsilon_0 \frac{d\phi_E}{dt} = \varepsilon_0 \frac{d(EA)}{dt} = \varepsilon_0 \frac{d}{dt}\left[\frac{q}{A\varepsilon_0}\cdot A\right]$$

$$\Rightarrow i_d = \varepsilon_0 \frac{d}{dt}\left(\frac{q}{\varepsilon_0}\right) = \frac{dq}{dt} = i_c$$

Properties of Displacement Current :-

- It's not a conventional current. As, it produces $\vec{B}$ ∴ Called disp current
- It exists only when there is change in $\vec{E}$ (ϕ_E)
- It doesn't exist under steady condⁿ (const $\vec{E}$)
- It satisfies the property of continuity, together with i_c.

MAXWELL'S EQUATIONS :-

All the basic principles of Electromagnetism can be explained in terms of four fundamental equations (in the absence of any dielectric or magnetic material):

(i) **Guass's Law of Electrostatics :-** Electric Flux through a closed surface is $\frac{1}{\varepsilon_0}$ times the total charge, 'q' enclosed by the surface.

$$\phi_E \text{ (closed)} = \frac{q_{enclosed}}{\varepsilon_0}$$

$$\Rightarrow \boxed{\oint_S \vec{E}\cdot d\vec{s} = \frac{q_{enclosed}}{\varepsilon_0}}$$

(ii) **Guass's Law of Magnetism :-** Net magnetic flux thro' a closed surface is zero.

$$\boxed{\oint_S \vec{B}\cdot d\vec{s} = 0} \qquad \phi_B \text{ (closed)} = 0$$

(iii) **Faraday's Law of Electromagnetic Induction :-**

- change in Magnetic flux induces an emf. $e = -\frac{d\phi_B}{dt}$ OR
- changing magnetic field induces an electric field.

The line integral of the electric field around any closed path (i.e. emf) is equal to the rate of change of mag. flux thro' any surface bounded by that path.

$$\boxed{\oint \vec{E}\cdot d\vec{l} = -\frac{d\phi_B}{dt}}$$

(iv) **Ampere - Maxwell's Law :-** The line integral of the mag. field around any closed path is determined by the sum of the net conduction current thro' that path & the rate of change of electric flux (ϕ_E) thro' any surface bounded by that path.

This Law describes how a mag. field can be produced by both changing ϕ_E (i_d) & a conduction current (i_c).

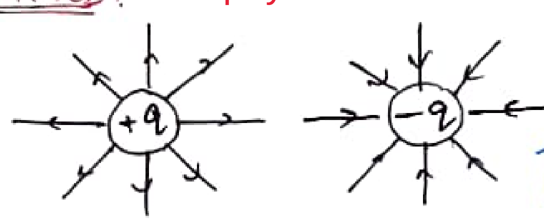
$$\boxed{\oint \vec{B}\cdot d\vec{l} = \mu_0 (i + i_d) = \mu_0 i + \mu_0 \varepsilon_0 \left(\frac{d\phi_E}{dt}\right)}$$

HOW ELETROMAGNETIC WAVES ARE FORMED?

$\vec{E}$ & $\vec{B}$ due to a charge:

Case-1: Charge at Rest

Electric Field.



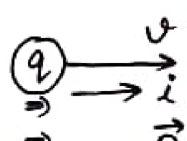
$i = 0$
$B = 0$

Case-2: Charge is moving with Uniform Velocity:

↳ free charge – $\vec{E}$ & $\vec{B}$

↳ bound charge – charge moving in a circuit

net $q = 0$ $\therefore \vec{E} = 0$



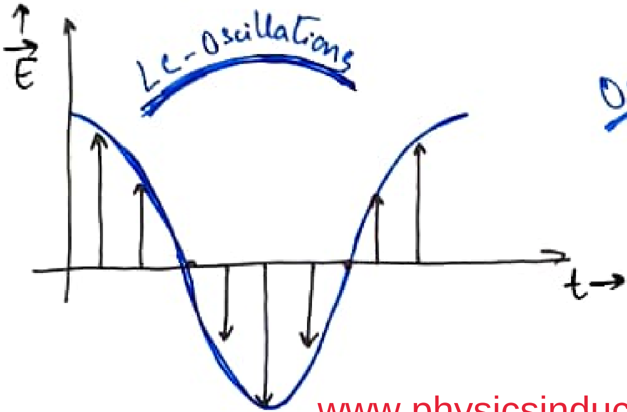
Case 3: Accelerated charged particle

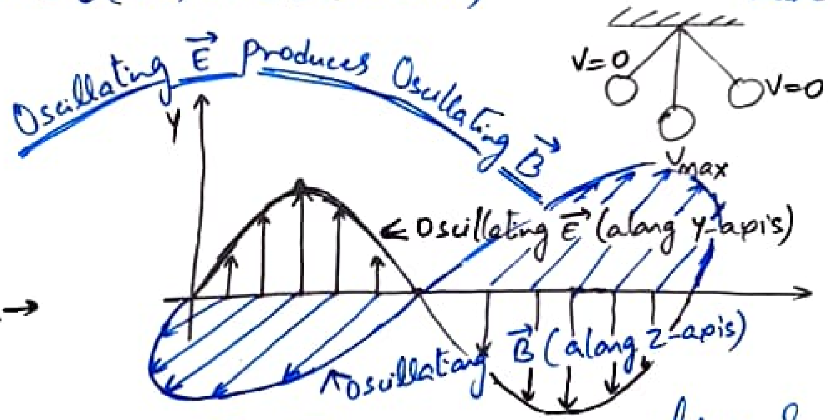
$q \longrightarrow v$ (variable velocity)

An accelerated charged particle produces a time varying $\vec{E}$ & $\vec{B}$. ↳ Electromagnetic Wave

(accelerated → Oscillating → L-C Oscillations)

$\vec{E}_{max}(q_0) \rightarrow \vec{E}\downarrow(q) \rightarrow \vec{E}=0 \rightarrow \vec{E}\downarrow(-ve) \rightarrow \vec{E}\downarrow(-ve\ maxm)$





$\vec{E}$ & $\vec{B}$ are in the same phase & they are self propagating.

ELECTROMAGNETIC WAVES ARE TRANSVERSE IN NATURE:–

EM waves are those waves in which there are sinusoidal variation of electric & magnetic field vectors at right angles to each other as well as at right angles to the direction of wave propagation.

$\vec{E} \perp$ Wave prop
$\vec{B} \perp$ Wave prop
$\uparrow$ $\vec{E}\times\vec{B}$

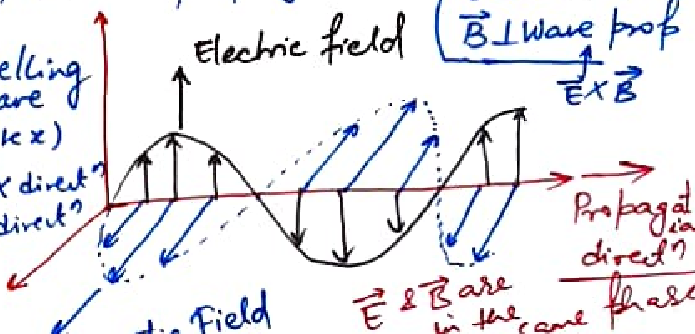
Eq^n of EM Wave :–

EM wave – Travelling wave

Gen eq^n: Traveling wave: $y = A\sin(\omega t \pm kx)$

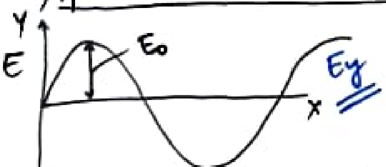
(+) → wave is travelling in −ve x direct^n
(−) → " " " " +ve x-direct^n

$y = f(x,t)$



$\vec{E}$ & $\vec{B}$ are in the same phase

1.) for Electric field, $\vec{E}$:



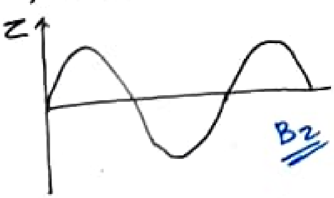
$$E = E_0\sin(kx-\omega t)$$

$$= E_0 \sin\left(\frac{2\pi}{\lambda}x - \frac{2\pi}{T}t\right) = E_0\sin\left[2\pi\left(\frac{x}{\lambda} - \frac{t}{T}\right)\right]$$

$$= E_0\sin\left[2\pi\left(\frac{x}{\lambda} - \nu t\right)\right]$$

2.) For Magnetic Field, $\vec{B}$:

$$B = B_0\sin(kx-\omega t) = B_0\sin\left(\frac{2\pi}{\lambda}x - \frac{2\pi}{t}T\right) = B_0\sin\left[2\pi\left(\frac{x}{\lambda} - \frac{t}{T}\right)\right]$$

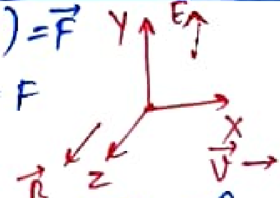


$q(\vec{E} + \vec{v}\times\vec{B}) = \vec{F}$

$q(E - vB)\hat{j} = F$

If $F = 0$

$\Rightarrow v = \dfrac{E}{B}$



$\vec{E} = E\hat{j}$
$\vec{v} = v\hat{i}$
$\vec{B} = B\hat{k}$

3) Speed of travelling wave, v

$$v = \frac{\omega}{k}$$

4) Peak value of $\vec{E}$ (E_0) & $\vec{B}$ (B_0):

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

Permeability & Permittivity of Medium:

- In EM waves, the oscillations of $\vec{E}$ & $\vec{B}$ are in the same phase
- The cross product $(\vec{E}\times\vec{B})$ tells the direct^n in which the

wave travels.

Now $(\varepsilon_0 \mu_0) = (4\pi\varepsilon_0)\left(\frac{\mu_0}{4\pi}\right) = \frac{1}{(9\times10^9)}(10^{-7}) = \frac{1}{(3\times10^8)^2} = \frac{1}{c^2}$

$$\Rightarrow \boxed{c = \frac{1}{\sqrt{\mu_0\varepsilon_0}}}$$

The speed of EM wave thro' a medium of permeability μ & permittivity ε is; $v = \frac{1}{\sqrt{\mu\varepsilon}}$

$$\Rightarrow v = \frac{1}{\sqrt{\mu\varepsilon_0}} = \frac{1}{\sqrt{\mu_r\mu_0\varepsilon_r\varepsilon_0}} = \frac{1}{\sqrt{\mu_0\varepsilon_0}\sqrt{\mu_r\varepsilon_r}} = \boxed{\frac{c}{\sqrt{\mu_r\varepsilon_r}}}$$

Average Energy Density :- u_{av}

for EMW $E, B \to$ rms

As, Average Electric energy density, $u_E = \frac{1}{2}\varepsilon_0 E^2$

& Average magnetic " " , $u_B = \frac{B^2}{2\mu_0}$

$\therefore$ Total Average Energy density (due to both the fields):

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

$E \to E_{rms} = \frac{E_0}{\sqrt{2}}$

& $B \to B_{rms} \to B_0/\sqrt{2}$

$$\Rightarrow u = \frac{1}{2}\varepsilon_0\frac{E_0^2}{2} + \frac{1}{2}\frac{B_0^2}{(2\mu_0)}$$

EMW →

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

(write $B_0 = \frac{E_0}{c}$)

$$u = \frac{1}{4}\varepsilon_0 E_0^2 + \frac{1}{4}\frac{E_0^2}{c^2\mu_0}$$

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

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

(write $E_0 = cB_0$)

$$u = \frac{1}{4}\varepsilon_0(cB_0)^2 + \frac{1}{4}\frac{B_0^2}{\mu_0}$$

$$= \frac{1}{4}\frac{\varepsilon_0 \cdot B_0^2}{\mu_0\varepsilon_0} + \frac{1}{4}\frac{B_0^2}{\mu_0}$$

$$= \frac{1}{2}\frac{B_0^2}{\mu_0}$$

$$\therefore u_{av} = u_E + u_B = 2u_E = 2u_B = 2\times\frac{1}{2}\varepsilon_0 E^2 = \varepsilon_0 E^2 = \frac{B^2}{\mu_0} = \frac{1}{2}\varepsilon_0 E_0^2 = \frac{1}{\mu_0}\frac{B_0^2}{2}$$

ELECTROMAGNETIC SPECTRUM

The orderly distribution of electromagnetic radiations according to their wavelength or frequency is called the Electromagnetic spectrum.

Increasing frequency (decreasing wavelength):

Order: Mnemonics: Russian (Radio Wares) Magicians (Microwares) Introduced (Infra-red) a Very (Visible light) Unusual (Ultra-violet) X-rays (X-rays) eye Game (Gamma Rays)

Radio Wares :-

$\nu : 5\times10^5 Hz - 3\times10^9 Hz$; $\lambda > 0.1 m$ (longest λ, minimum ν)

Uses :- (i) Radio & T.V. communication system

(ii) Radioastronomy

530 KHz – 1710 KHz : AM (Amplitude modulated) band

1710 KHz – 54 MHz : short wave AM Band

54 MHz – 890 MHz : TV wares

88 MHz – 108 MHz : FM Radio Band

300 MHz – 3000 MHz : Ultra High freq. (UHF) Band.

Discovered by : Marconi (1895)

Propertes : Reflection, Diffraction

Source : Accelerated q particles in conducting wires or oscillating circuits.

detected by Receiver aerials

Micro Wares :-

$\nu : 3\times10^9 Hz - 3\times10^{11} Hz$; $\lambda : 0.1 m - 1 mm$

(i) In RADAR system for aircraft navigation.

(ii) A radar using microware can help in detecting the speed of tennis ball, cricket ball, automobiles.

(iii) for observing movement of trains on rails while sitting in microware operated control rooms.

(iv) Microware ovens are used for cooking purposes

Discovered by : Marconi (1895)

Properties : Reflection, Refraction, diffraction & polarisation.

Source : by Vacuum tubes

detected by pt-contact diodes

Infra-red wares :-

$\nu : 3\times10^{11} Hz - 4\times10^{14} Hz$; λ : 1 mm – 700 nm

(heat wares)

(i) in Physical therapy (muscular strain)

(ii) for dehydrating fruits

(iii) In green houses to keep the plants

Discovered by : William Hershell (1800)

Properties : Heating effect, Reflection, Refraction, Diffraction & propagation through fog

Source : Hot Objects, Vibrations of atoms & molecules warm.

(iv) to provide electrical energy to satellites using solar cells
(v) for taking photographs, at the time of fog, smoke etc.
(vi) In solar water heaters & cookers.
(vii) In revealing the secret writings as ancient walls.
(viii) in knowing the molecular structure.
(ix) in checking the purity of chemicals
(x) in eye-surgery.
(xi) in weather forecasting thro' infra-red photography.
(xii) in haze photography b'coz IR waves are less scattered than visible light

detected by Thermopile, Bolometer, IR photographic plate

Visible light:- $\nu: 4\times10^{14}Hz - 8\times10^{14}Hz$; λ: 700 nm – 400 nm

(i) chemical Reactions
(ii) in photography to take the picture of objects.
(iii) in astronomy to track the movement of heavenly bodies
(iv) in optical microscopy which involves the study of minute objects.

Properties: Reflection, Refraction, Interference, Diffraction, polarisation, Photoelectric effect, photographic Action, sensation of sight.
Source: excitation of valence e^- in atoms.

Ultraviolet Rays:- $\nu: 8\times10^{14}Hz - 3\times10^{17}Hz$; λ: 400 nm – 1 nm

(i) food preservation
(ii) in the study of invisible writings, forged documents and finger prints.
(iii) in the study of molecular structure
(iv) in burglar alarm
(v) to kill germs in water purifier.
(vi) in Lasik eye surgery.
(vii) to destroy the bacteria and for sterlizing the surgical instruments.
(viii) for checking the mineral samples thro' the prop. of UV rays causing flourescence

Discovered by: Ritter (1800)
Properties: Effect on photographic plate, fluorescence, ionisation, highly energetic, tanning of skin
Source: High voltage gas discharge tubes, arcs of iron & Hg, the Sun.

detected by photocells, photographic film

X-rays :- ν : 3×10^{17} Hz − 3×10^{20} Hz λ : 1 nm − 10^{-3} nm

(i) In surgery, detection of fractures, foreign bodies like bullets, diseased organs & stones
(ii) for detecting faults, cracks, flaws & holes
(iii) to cure untraceable skin diseases & malignant growths.
(iv) for detection of explosives, opium, gold & silver
(v) for the detection of pearls in oysters & defects in rubber tyres, gold & tennis balls
(vi) cause photoelectric emission from metals

Discovered by : W. Roentgen (1895)
Source : Sudden deceleration of fast moving e^- by a metal target
Properties : effect on photographic plate, ionisation of gases, photoelectric effect, fluorescence, more energetic than UV rays.
detected by photographic film, Geiger tubes, Ionization chamber

γ-Rays :- ν : 3×10^{18} Hz − 5×10^{23} Hz, $\lambda < 10^{-3}$ nm
highly energetic

(i) treatment of cancer & tumours
(ii) to produce nuclear reactions
(iii) to study the structure of atomic nuclei
(iv) to preserve the food stuffs for a long time as the soft γ-rays can kill micro-org. easily

Discovered by : Henry Becquerel (1896)
Source : Radioactive nuclei & nuclear reactions. Co-60 is a pure γ-ray source.
Properties : Effect on photographic plate, fluorescence, Ionisation, diffraction, high penetrating power
detected by photographic film, Geiger tubes, Ionization chamber

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