FREE NOTES · NCERT + JEE/NEET LEVEL

Electromagnetic Waves

Displacement current, Maxwell's equations, properties of EM waves, their speed, energy and momentum, and the full electromagnetic spectrum with uses.

01 Displacement current
02 Maxwell's equations
03 What is an EM wave
04 Properties of EM waves
05 Energy, intensity & momentum
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01 Displacement current

While a capacitor charges, current flows in the wire but no charge flows between the plates. Yet there is a magnetic field between the plates. Maxwell explained: **a changing electric field also acts like a current**.

$$I_d = \varepsilon_0 \, d\Phi_E/dt$$

Displacement current = conduction current (while charging). Ampere-Maxwell law: $\oint B \cdot dl = \mu_0(I_c + I_d)$.

WHAT IT MEANS

A changing B ⇒ E (Faraday). A changing E ⇒ B (Maxwell). Each creates the other as they travel: that is an **EM wave**.

02 Maxwell's equations

Equation	Name	Meaning
$\oint E \cdot dA = Q/\varepsilon_0$	Gauss (electricity)	Charges create field
$\oint B \cdot dA = 0$	Gauss (magnetism)	No monopoles
$\oint E \cdot dl = -d\Phi_B/dt$	Faraday	Changing B ⇒ E
$\oint B \cdot dl = \mu_0 I + \mu_0\varepsilon_0 \, d\Phi_E/dt$	Ampere-Maxwell	Current or changing E ⇒ B

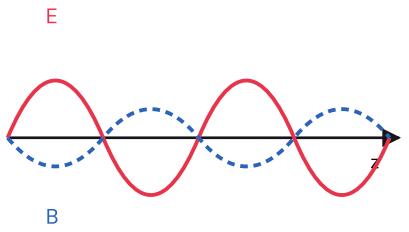
03 What is an EM wave

An **accelerated (or oscillating) charge** produces EM waves. A charge at rest gives only E; a charge at constant speed gives E and B; only an accelerated charge radiates a wave.

$$E_x = E_0 \sin(kz - \omega t)$$

$$B_y = B_0 \sin(kz - \omega t)$$

E, B and the direction of travel are mutually perpendicular. E and B are in phase. Direction = E × B.



E and B perpendicular, both ⊥ to the direction of travel (z)

04 Properties of EM waves

- **Transverse** waves.
- **Need no medium**; fastest in vacuum.
- Speed in vacuum $c = 1/\sqrt{(\mu_0\varepsilon_0)} = 3 \times 10^8\ \mathrm{m/s}$, the same for all frequencies.
- In a medium $v = 1/\sqrt{(\mu\varepsilon)} = c/n$, n = refractive index = $\sqrt{(\mu_r\varepsilon_r)}$.
- $E_0/B_0 = c$ (E looks larger but the energy is shared equally).
- They carry no charge, so electric or magnetic fields don't deflect them.

05 Energy, intensity & momentum

Energy density $u = \frac{1}{2}\varepsilon_0 E^2 + B^2/(2\mu_0)$; the two parts are equal

Average $u = \frac{1}{2}\,\varepsilon_0\,E_0^2$

$$\text{Intensity } I = u_{avg} \times c = \frac{1}{2}\,\varepsilon_0\,E_0^2\,c$$

Momentum $p = U/c$

Radiation pressure: fully absorbed ⇒ I/c, fully reflected ⇒ 2I/c. That's why sunlight gives a tiny push (a comet's tail points away from the Sun).

06 Electromagnetic spectrum

Wave	Wavelength (approx.)	Produced by	Uses
Radio	> 0.1 m	Oscillating current in an antenna	Radio, TV, mobile phones
Microwave	0.1 m – 1 mm	Klystron, magnetron	Radar, microwave oven, satellites
Infrared	1 mm – 700 nm	Hot bodies, molecular vibrations	Remote controls, night vision, physiotherapy, "heat waves"
Visible	700 – 400 nm	Electron jumps in atoms	Vision (red longest, violet shortest)
Ultraviolet	400 – 1 nm	The Sun, very hot bodies	Water purification, LASIK; ozone protects us from it
X-rays	1 nm – 10^{-3} nm	Fast electrons hitting a metal	Bone imaging, cancer treatment
Gamma rays	< 10^{-3} nm	Nuclei (radioactivity)	Cancer treatment, food sterilisation

REMEMBERING THE ORDER

In decreasing wavelength: **R**adio, **M**icro, **I**nfrared, **V**isible, **U**V, **X**, **G**amma, i.e. **R–M–I–V–U–X–G**. Frequency and energy increase in this order.

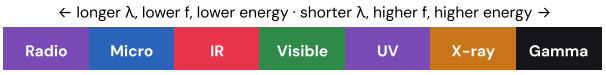
GREENHOUSE EFFECT

The warm Earth emits infrared; gases like CO_2 trap it ⇒ the Earth stays warm.

07 JEE Extra + Tricks

JEE LEVEL

- $c = 1/\sqrt{(\mu_o \varepsilon_o)}$; $E_o = cB_o$; E, B and direction of travel are mutually perpendicular (E × B gives direction).
- Displacement current $I_d = \varepsilon_o \, d\Phi_E/dt$ (makes Ampère's law consistent inside a charging capacitor).
- Average energy density $u = \frac{1}{2}\varepsilon_o E_o^2$ (shared equally by E and B); intensity $I = u \cdot c$.
- Radiation pressure: fully absorbed I/c, fully reflected 2I/c.



Visible: 400 nm (violet) to 700 nm (red)
Trick: "Ram's Mother Is Visiting Uncle X-ray Gamma"

Electromagnetic spectrum

08 Solved numericals

Q1. An EM wave has E_o = 60 V/m. B_o?
$B_o = E_o/c = 60/(3 \times 10^8) = 2 \times 10^{-7}$ T. **Ans: 2×10^{-7} T**

Q2. Wavelength of a 30 MHz radio wave?
$\lambda = c/f = 3 \times 10^8/3 \times 10^7 = 10$ m. **Ans: 10 m**

Q3. Capacitor plates of area 0.01 m², E changing at 10^{12} V/m·s. Displacement current? ($\varepsilon_o = 8.85 \times 10^{-12}$)
$I_d = \varepsilon_o A\, dE/dt = 8.85 \times 10^{-12} \times 0.01 \times 10^{12} = 0.0885$ A. **Ans: ≈ 88.5 mA**

Q4. Speed of light in glass (ε_r = 2.25, μ_r = 1)?
$n = \sqrt{2.25} = 1.5 \Rightarrow v = 2 \times 10^8$ m/s. **Ans: 2×10^8 m/s**

09 Common mistakes

- Thinking E and B are 90° out of phase. They are in phase; only their directions are perpendicular.
- Thinking a uniformly moving charge radiates (it must accelerate).
- Thinking different frequencies travel at different speeds in vacuum.
- Getting the spectrum order wrong (mixing UV/X-ray or IR/microwave).

10 Formula sheet

Displacement current	$I_d = \varepsilon_0\, d\Phi_E/dt$
Speed	$c = 1/\sqrt{(\mu_0\varepsilon_0)}$, $v = c/n$
Field ratio	$E_0/B_0 = c$
Wave relation	$c = f\lambda$
Intensity	$I = \frac{1}{2}\varepsilon_0 E_0^2 c$
Momentum	$p = U/c$
Radiation pressure	I/c (absorbed), $2I/c$ (reflected)

11 Practice questions

1. Which EM wave carries the most energy?
2. Which wave does a TV remote use?
3. Which wave does the ozone layer block?
4. $B_o = 10^{-8}$ T. E_o?

ANSWERS

1) Gamma rays · 2) Infrared · 3) Ultraviolet · 4) 3 V/m

12 Quick revision: 5 minutes before the exam

BASICS

- $I_d = \varepsilon_o \, d\Phi_E/dt$.
- Accelerated charge ⇒ EM wave.
- Transverse, no medium needed.

NUMBERS

- $c = 1/\sqrt{(\mu_o \varepsilon_o)} = 3 \times 10^8$.
- $E_o = cB_o$; in phase.
- $I = \frac{1}{2}\varepsilon_o E_o^2 c$.

SPECTRUM

- Radio > micro > IR > visible > UV > X > γ (λ).
- Energy in the reverse order.

USES

- Microwave: radar, oven.
- IR: remotes, heat.
- X-ray: bones; γ: cancer.

Have a doubt? Ask the AI Doubt Solver at padhaiadda.netlify.app, or take the mock test on this chapter.