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ELECTROMAGNETIC WAVES

Displacement Current

1. Displacement current (I_D) is defined as:

$$I_D = \epsilon_0 \frac{d\Phi_E}{dt}$$

where Φ_E represents the time-varying electric flux between capacitor plates.

2. Ampere-Maxwell's law becomes:

$$\oint \vec{B} \cdot d\vec{l} = \mu_0 \left(I_C + \epsilon_0 \frac{d\Phi_E}{dt} \right)$$

3. Displacement current equals conduction current: $I_D = I_C$.
4. Displacement current also produces magnetic field.

Generation of Electromagnetic Waves

- Accelerated charges create time-varying magnetic fields.
- These in turn generate varying electric fields.
- The two fields sustain and regenerate each other, forming a transverse wave.

Properties of Electromagnetic Waves

1. Satisfy wave equations:

$$\frac{\partial^2 E}{\partial x^2} = \mu_0 \epsilon_0 \frac{\partial^2 E}{\partial t^2}, \quad \frac{\partial^2 B}{\partial x^2} = \mu_0 \epsilon_0 \frac{\partial^2 B}{\partial t^2}$$

2. Transverse in nature; \vec{E} and \vec{B} are perpendicular to each other and direction of propagation.

3. Speed in vacuum:

$$c = \frac{1}{\sqrt{\mu_0 \epsilon_0}} = 3 \times 10^8 \text{ m/s}$$

4. Speed in medium: $v = \frac{1}{\sqrt{\mu \epsilon}}$

5. Amplitude ratio:

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

6. Carry both energy and momentum.

7. Do not need medium for propagation.

8. The electric and magnetic fields of a sinusoidal EM wave propagating in $+x$ direction are:

$$\mathbf{E} = E_m \sin(kx - \omega t), \quad \mathbf{B} = B_m \sin(kx - \omega t)$$

where angular frequency and wave number are:

$$\omega = 2\pi f, \quad k = \frac{2\pi}{\lambda}$$

9. Intensity is the time-averaged Poynting vector over one cycle:

$$S_{av} = \frac{E_m B_m}{2\mu_0} = \frac{E_m^2}{2\mu_0 c} = \frac{c}{2\mu_0} = \frac{B_m^2}{2}$$

10. Unaffected by external electric/magnetic fields.

11. Exhibit reflection, refraction, interference, diffraction, and polarization.

Electromagnetic Spectrum

The EM spectrum arranges radiations by increasing frequency or decreasing wavelength.

Name	Discoverer	Source	Wavelength	Frequency	Energy	Uses / Features
Gamma Rays	Becquerel	Nuclear Decay	$10^{-14}\text{m} - 10^{-10}\text{m}$	$3 \times 10^{22} - 3 \times 10^{18}$ Hz	$10^8 - 10^4$ eV	Cancer treatment, nuclear reactions
X-Rays	Roentgen	Fast Electron Deceleration	$10^{-12} - 10^{-8}$ m	$3 \times 10^{20} - 3 \times 10^{16}$ Hz	$10^6 - 10^2$ eV	Imaging, flaw detection, crystal analysis
UV Rays	Ritter	Sun, Hg Lamp	$10^{-8} - 4 \times 10^{-7}$ m	$3 \times 10^{16} - 7.5 \times 10^{14}$ Hz	$10^2 - 1$ eV	Sterilization, security marking, water purification
Visible Light	Newton	Hot Bodies	$4 \times 10^{-7} - 7.8 \times 10^{-7}$ m	$7.5 \times 10^{14} - 3.8 \times 10^{14}$ Hz	$1 - 0.5$ eV	Human vision, photography, photosynthesis
IR Rays	Herschel	Warm Objects	$7.8 \times 10^{-7} - 10^{-3}$ m	$3.8 \times 10^{14} - 3 \times 10^{11}$ Hz	$0.5 - 10^{-3}$ eV	Remote controls, thermal cameras, night vision
Microwaves	Hertz	Klystron / Magnetron	$10^{-3} - 0.3$ m	$3 \times 10^{11} - 10^9$ Hz	$10^{-3} - 10^{-5}$ eV	Cooking, radar, satellite communication
Radio Waves	Marconi	Oscillators	0.3 m to km	10^9 Hz to few Hz	10^{-5} eV to ~ 0	Radio, TV, communication

Radio Wave Sub-bands:

Band	Wavelength	Frequency	Application
SHF (Super High)	0.01–0.1 m	$3 \times 10^{10} - 3 \times 10^9$ Hz	Short-range links
UHF (Ultra High)	0.1–1 m	$3 \times 10^9 - 3 \times 10^8$ Hz	TV broadcasting
VHF (Very High)	1–10 m	$3 \times 10^8 - 3 \times 10^7$ Hz	TV and FM radio
HF (High Freq)	10–100 m	$3 \times 10^7 - 3 \times 10^6$ Hz	Shortwave radio

MF (Medium Freq)	100–1000 m	3×10^6 – 3×10^5 Hz	AM broadcast
LF (Low Freq)	1–10 km	3×10^5 – 3×10^4 Hz	Submarine/nav systems