

Chapter 8 : Electromagnetic Waves (Notes)

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Notes

GSEB and CBSE Board Exam preparation subjective notes · Class 12 Physics · NCERT Chapter 8

Q.1 What inconsistency did Maxwell find in Ampere's circuital law? (3 Marks) Explain with the charging of a capacitor.

Ampere's circuital law states

$$\oint \vec{B} \cdot d\vec{l} = \mu_0 i(t)$$

Consider a parallel plate capacitor C in a circuit through which a time-dependent current $i(t)$ flows (Fig. 8.1). We find the magnetic field at a point P outside the capacitor, using a circular loop of radius r through P, perpendicular to the wire and centred on it.

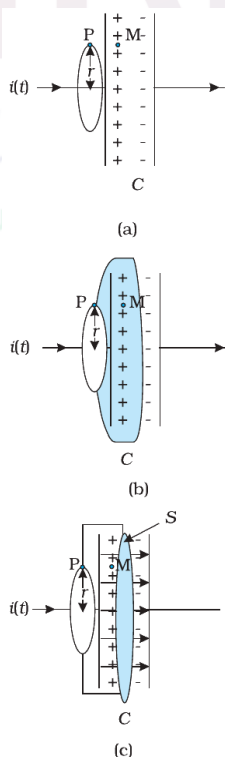


Fig. 8.1: A parallel plate capacitor C in a circuit carrying a time-dependent current $i(t)$. (a) A loop of radius r through P; (b) a pot-shaped surface through the interior between the plates with the loop as its rim; (c) a tiffin-shaped surface with a flat circular bottom S between the plates

Surface 1 (flat disc, Fig. 8.1(a)): The current i passes through it. By symmetry, B is tangential and constant on the loop:

$$B(2\pi r) = \mu_0 i(t) \Rightarrow B = \frac{\mu_0 i}{2\pi r}$$

Surface 2 (pot-shaped, Fig. 8.1(b) and (c)): It has the same boundary, but its bottom lies between the capacitor plates, so **no current** passes through it. Ampere's law then gives $B = 0$ at P.

Contradiction: Calculated one way there is a magnetic field at P; calculated another way it is zero. So Ampere's law is **incomplete** — something is missing for time-varying fields.

Key Examination Points for Full Marks:

- The magnetic field at P must be the same whichever surface is used.
- The missing term is related to the **changing electric field** between the plates.

Q.2 Define displacement current. Derive its expression and write the Ampere–Maxwell law. (3 Marks)

Between the plates of the capacitor, there is no conduction current, but there is an **electric field**. If the plates have area A and charge Q, the field is $E = \frac{Q}{\epsilon_0 A}$, perpendicular to the surface S of Fig. 8.1(c). The electric flux through S is

$$\Phi_E = \left| \vec{E} \right| A = \frac{1}{\epsilon_0} \frac{Q}{A} A = \frac{Q}{\epsilon_0}$$

If Q changes with time, the current is $i = dQ/dt$, so

$$\frac{d\Phi_E}{dt} = \frac{1}{\epsilon_0} \frac{dQ}{dt} \Rightarrow \epsilon_0 \frac{d\Phi_E}{dt} = i$$

This is the missing term. Maxwell called it the **displacement current**:

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

The **conduction current** i_c is due to the flow of charges; the displacement current is due to a **changing electric field** (electric displacement). The total current is

$$i = i_c + i_d = i_c + \epsilon_0 \frac{d\Phi_E}{dt}$$

Ampere–Maxwell law:

$$\oint \vec{B} \cdot d\vec{l} = \mu_0 i_c + \mu_0 \epsilon_0 \frac{d\Phi_E}{dt}$$

Outside the capacitor plates, $i_c = i$ and $i_d = 0$; inside, $i_c = 0$ and $i_d = i$. The magnetic field at M between the plates (Fig. 8.2) is the same as just outside at P.

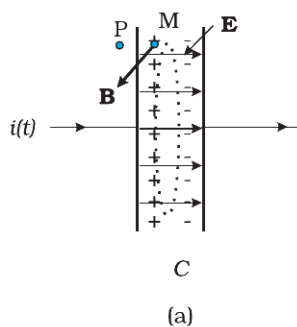


Fig. 8.2(a): The electric and magnetic fields E and B between the capacitor plates, at the point M

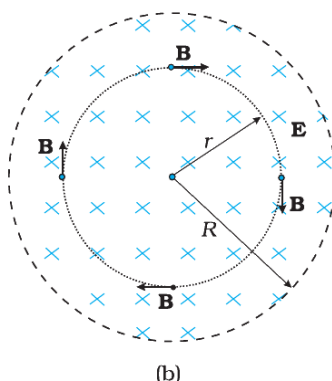


Fig. 8.2(b): A cross-sectional view of Fig. (a)

Key Examination Points for Full Marks:

- The displacement current has the **same physical effects** as conduction current — it produces a magnetic field.
- It is zero for steady electric fields (dc in a wire).
- Symmetry:** a changing magnetic field produces an electric field (Faraday); a changing electric field produces a magnetic field (Maxwell). This leads to electromagnetic waves.

Q.3 Write Maxwell's equations in vacuum.**(2 Marks)**

Law	Equation
1. Gauss's law for electricity	$\oint \vec{E} \cdot d\vec{A} = \frac{Q}{\epsilon_0}$
2. Gauss's law for magnetism	$\oint \vec{B} \cdot d\vec{A} = 0$
3. Faraday's law	$\oint \vec{E} \cdot d\vec{l} = -\frac{d\Phi_B}{dt}$
4. Ampere–Maxwell law	$\oint \vec{B} \cdot d\vec{l} = \mu_0 i_c + \mu_0 \epsilon_0 \frac{d\Phi_E}{dt}$

Together with the **Lorentz force** formula, these express all the basic laws of electromagnetism.

Key Examination Points for Full Marks:

- The laws are still not perfectly symmetric: there are no known **magnetic monopoles** (sources of B analogous to charges).
- The most important prediction of Maxwell's equations is the existence of **electromagnetic waves** travelling with speed $c = 1/\sqrt{\mu_0 \epsilon_0}$.

Q.4 How are electromagnetic waves produced? Why could Hertz not use visible light to test Maxwell's theory? (2 Marks)

Sources: Neither stationary charges (which produce only electrostatic fields) nor charges in uniform motion (steady currents, which produce constant magnetic fields) radiate. **Accelerated charges radiate electromagnetic waves.**

Consider a charge oscillating with some frequency (an oscillating charge is accelerating). It produces an oscillating electric field, which produces an oscillating magnetic field, which in turn produces an oscillating electric field, and so on. The fields **regenerate each other** as the wave propagates. The frequency of the wave equals the frequency of oscillation of the charge. The energy of the wave comes from the source.

Hertz's experiment (1887): The frequency of yellow light is about 6×10^{14} Hz, while even modern electronic circuits reach hardly 10^{11} Hz. So the experimental demonstration had to use the **low-frequency radio region**.

Hertz produced and detected EM waves of wavelength of a few metres.

Later work: J.C. Bose (Kolkata) produced EM waves of wavelength 25 mm to 5 mm. Marconi transmitted EM waves over many kilometres — the beginning of wireless communication.

Key Examination Points for Full Marks:

- An electric dipole oscillating harmonically is a basic source of EM waves.
- A transmitting antenna radiates most efficiently at wavelengths comparable to its own size.

Q.5 Describe the nature of electromagnetic waves. Write the equations of a plane EM wave. (3 Marks)

From Maxwell's equations, the electric and magnetic fields in an EM wave are **perpendicular to each other and to the direction of propagation** — EM waves are **transverse**.

For a plane EM wave travelling along z , with $\vec{E}$ along x and $\vec{B}$ along y (Fig. 8.3):

$$E_x = E_0 \sin(kz - \omega t), \quad B_y = B_0 \sin(kz - \omega t)$$

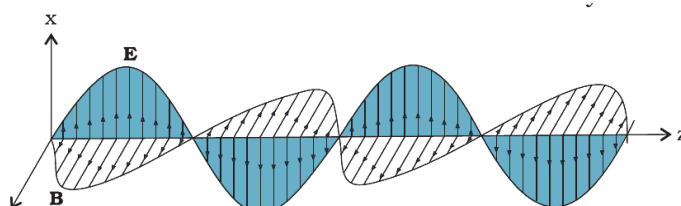


Fig. 8.3: A linearly polarised electromagnetic wave travelling in the z -direction, with E along x and B along y

where $k = \frac{2\pi}{\lambda}$ is the **wave number** (propagation vector $\vec{k}$ points along the direction of propagation) and ω the angular frequency.

Speed of EM waves:

$$\omega = ck, \quad c = \frac{1}{\sqrt{\mu_0 \epsilon_0}} = 3 \times 10^8 \text{ m/s}, \quad \nu\lambda = c$$

Relation between field amplitudes:

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

Properties of EM waves:

- i. They are self-sustaining oscillations of E and B and **need no material medium**.
- ii. $\vec{E}$, $\vec{B}$ and the direction of propagation are mutually perpendicular; the wave travels along $\vec{E} \times \vec{B}$.
- iii. $\vec{E}$ and $\vec{B}$ oscillate **in phase** with the same frequency.
- iv. The speed in vacuum is the same for all wavelengths: $c = 3 \times 10^8 \text{ m/s}$.
- v. They carry **energy** and **momentum**, and exert **radiation pressure**.
- vi. The average energy densities of the electric and magnetic fields are equal.

In a medium of permittivity ϵ and permeability μ :

$$v = \frac{1}{\sqrt{\mu\epsilon}} = \frac{c}{\sqrt{\mu_r \epsilon_r}}$$

So the velocity of light depends on the electric and magnetic properties of the medium.

Key Examination Points for Full Marks:

- The plane of polarisation is defined by the direction of $\vec{E}$.

- **Example 8.1:** 25 MHz along x with $\vec{E} = 6.3\hat{j}$ V/m: $B = E/c = 2.1 \times 10^{-8}$ T along $\hat{k}$.
- **Example 8.2:** $B_y = 2 \times 10^{-7} \sin (0.5 \times 10^3 x + 1.5 \times 10^{11} t)$: $\lambda = 126$ cm, $\nu = 23.9$ GHz, $E_0 = 60$ V/m along z.

Q.6 Show that an electromagnetic wave carries energy and momentum. (2 Marks)

What is radiation pressure?

Energy: An EM wave carries energy in its electric and magnetic fields. The energy densities are

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

Since $E = cB$ and $c^2 = 1/\mu_0\epsilon_0$, $u_E = u_B$. The average total energy density is

$$\bar{u} = \frac{1}{2}\epsilon_0 E_0^2, \quad \text{intensity } I = \bar{u}c = \frac{1}{2}c\epsilon_0 E_0^2$$

Radio and TV signals carry energy; light carries energy from the sun to the earth, making life possible.

Momentum: If a wave delivers energy U to a surface in time t , it also delivers momentum

$$p = \frac{U}{c} \quad (\text{complete absorption}), \quad p = \frac{2U}{c} \quad (\text{complete reflection})$$

Radiation pressure: The force per unit area exerted by the wave:

$$P = \frac{I}{c} \quad (\text{absorption}), \quad P = \frac{2I}{c} \quad (\text{reflection})$$

Key Examination Points for Full Marks:

- We do not feel the pressure of sunlight because the energy (and so momentum) delivered per second is very small.
- The electric and magnetic fields contribute equally to the intensity.

Q.7 Describe the electromagnetic spectrum. Give the production and uses of radio waves and microwaves. (3 Marks)

Electromagnetic spectrum: The classification of EM waves according to frequency (or wavelength). There is **no sharp division** between one kind of wave and the next; the classification is based roughly on how the waves are produced and detected.

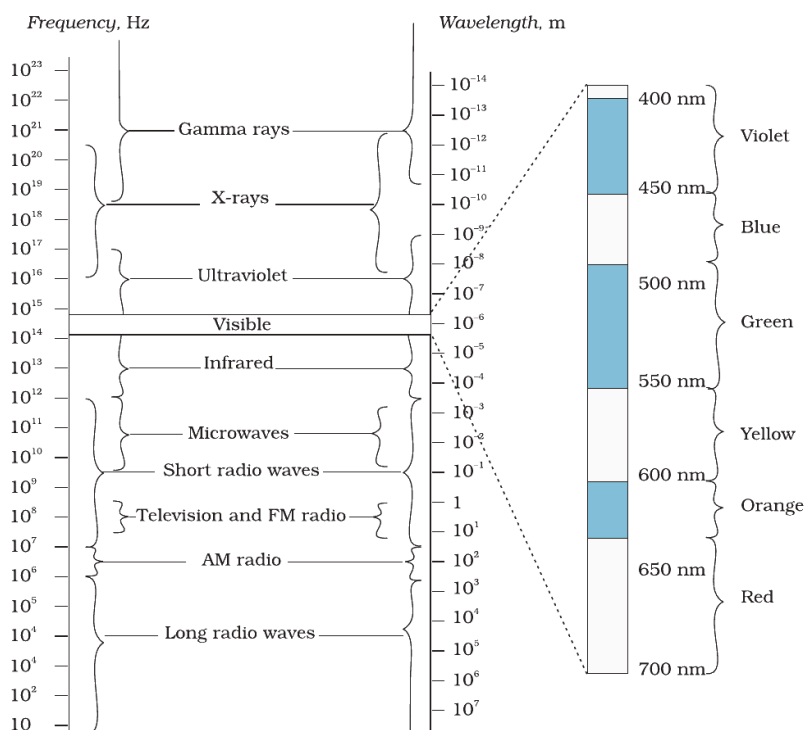


Fig. 8.4: The electromagnetic spectrum with common names for its parts. The regions do not have sharply defined boundaries

Radio waves ($\lambda > 0.1$ m):

- **Production:** accelerated motion of charges in conducting wires (rapid acceleration/deceleration of electrons in aerials).
- **Uses:** radio and TV communication. AM band: 530 kHz to 1710 kHz; short wave up to 54 MHz; TV: 54 MHz to 890 MHz; FM band: 88 MHz to 108 MHz. Cellular phones use the **UHF** band.

Microwaves (0.1 m to 1 mm, GHz frequencies):

- **Production:** special vacuum tubes — **klystrons, magnetrons and Gunn diodes**.
- **Uses:** radar systems in aircraft navigation; speed guns; **microwave ovens** — the frequency is matched to the **resonant frequency of water molecules**, so energy is efficiently transferred to their kinetic energy and the food heats up.

Key Examination Points for Full Marks:

- The basic difference between EM waves is their wavelength or frequency; all travel in vacuum with the same speed.
- Order of decreasing wavelength: radio > microwave > infrared > visible > UV > X-rays > γ -rays.

Q.8 Give the production, properties and uses of infrared, visible and ultraviolet rays. (3 Marks)

Infrared waves (1 mm to 700 nm):

- **Produced** by hot bodies and molecules (vibration of atoms and molecules).
- Called **heat waves**, because water molecules (and CO_2 , NH_3) readily absorb infrared, increasing their thermal motion and heating the surroundings.
- **Uses:** infrared lamps in **physical therapy**; the **greenhouse effect** (infrared re-radiated by the earth is trapped by CO_2 and water vapour, keeping the earth warm); infrared detectors in satellites (military use, observing crops); LEDs in **remote controls** of TVs and other appliances.

Visible rays (700 nm to 400 nm; 4×10^{14} Hz to 7×10^{14} Hz):

- Detected by the human eye; gives us information about the world. Snakes can detect infrared; the visible range of many insects extends into the ultraviolet.

Ultraviolet rays (400 nm to 0.6 nm):

- **Produced** by special lamps and very hot bodies; the **sun** is an important source. Most of the sun's UV is absorbed by the **ozone layer** (40–50 km altitude).
- Large amounts are **harmful**; exposure causes more melanin to be produced (**tanning**). UV is absorbed by ordinary glass, so one cannot get tanned through glass windows.
- **Uses:** welders wear special glass goggles; UV can be focussed into narrow beams for **LASIK eye surgery**; UV lamps **kill germs** in water purifiers.

Key Examination Points for Full Marks:

- Depletion of the ozone layer by CFCs (e.g. freon) is a matter of international concern.
- The centre of sensitivity of our eyes coincides with the strongest wavelengths of sunlight.

Q.9 Give the production and uses of X-rays and gamma rays. Summarise (3 Marks) the types of EM waves in a table.

X-rays (10 nm to 10^{-4} nm):

- **Produced** by bombarding a metal target with high-energy electrons (X-ray tubes), or by transitions of inner-shell electrons.
- **Uses:** diagnostic tool in medicine; treatment of certain forms of cancer. They damage living tissue, so over-exposure must be avoided.

Gamma rays (10^{-10} m to less than 10^{-14} m):

- Highest frequency; produced in **nuclear reactions** and emitted by **radioactive nuclei**.
- **Uses:** in medicine to destroy cancer cells.

Table 8.1: Different types of electromagnetic waves

Type	Wavelength range	Production	Detection
Radio	> 0.1 m	Rapid acceleration/deceleration of electrons in aerials	Receiver's aerials
Microwave	0.1 m to 1 mm	Klystron or magnetron valve	Point-contact diodes
Infrared	1 mm to 700 nm	Vibration of atoms and molecules	Thermopiles, bolometer, infrared film
Light	700 nm to 400 nm	Electrons in atoms moving to a lower energy level	The eye, photocells, photographic film
Ultraviolet	400 nm to 1 nm	Inner-shell electrons moving to a lower level	Photocells, photographic film
X-rays	1 nm to 10^{-3} nm	X-ray tubes or inner-shell electrons	Photographic film, Geiger tubes, ionisation chamber
Gamma rays	< 10^{-3} nm	Radioactive decay of the nucleus	As for X-rays

Key Examination Points for Full Marks:

- The wavelength is often related to the size of the radiating system: γ -rays (10^{-14} – 10^{-15} m) from nuclei; X-rays from heavy atoms; radio waves from antennas.

Formula Sheet — Electromagnetic Waves

Quantity	Formula	SI Unit
Displacement current	$i_d = \epsilon_0 \frac{d\Phi_E}{dt} = C \frac{dV}{dt}$	A
Ampere–Maxwell law	$\oint \vec{B} \cdot d\vec{l} = \mu_0 (i_c + i_d)$	T m
Plane wave	$E_x = E_0 \sin(kz - \omega t),$ $B_y = B_0 \sin(kz - \omega t)$	—
Speed in vacuum	$c = \frac{1}{\sqrt{\mu_0 \epsilon_0}} = \frac{\omega}{k} = \nu \lambda$	m s ⁻¹
Speed in a medium	$v = \frac{1}{\sqrt{\mu \epsilon}} = \frac{c}{\sqrt{\mu_r \epsilon_r}}; n = \sqrt{\mu_r \epsilon_r}$	m s ⁻¹
Field relation	$E_0 = cB_0$	—
Wave number	$k = \frac{2\pi}{\lambda}$	m ⁻¹
Energy densities	$u_E = \frac{1}{2}\epsilon_0 E^2 = u_B = \frac{B^2}{2\mu_0}$	J m ⁻³
Average energy density	$\bar{u} = \frac{1}{2}\epsilon_0 E_0^2 = \epsilon_0 E_{rms}^2$	J m ⁻³
Intensity	$I = \frac{1}{2}c\epsilon_0 E_0^2 = \frac{P}{4\pi r^2}$ (point source)	W m ⁻²
Momentum delivered	$p = \frac{U}{c}$ (absorbed), $\frac{2U}{c}$ (reflected)	kg m s ⁻¹
Radiation pressure	$\frac{I}{c}$ (absorbed), $\frac{2I}{c}$ (reflected)	N m ⁻²
Photon energy	$E = h\nu = \frac{hc}{\lambda}; E \text{ (eV)} = \frac{1240}{\lambda \text{ (nm)}}$	J, eV

Constants: $\mu_0 = 4\pi \times 10^{-7} \text{ T m A}^{-1}$; $\epsilon_0 = 8.85 \times 10^{-12} \text{ C}^2 \text{ N}^{-1} \text{ m}^{-2}$; $c = 3 \times 10^8 \text{ m s}^{-1}$.

Dimensions: $\mu_0 \epsilon_0$ [L⁻² T²]; $1/\mu_0 \epsilon_0 = (\text{velocity})^2$; displacement current [A].

NEET / JEE Quick Points and Tricks

- Direction rule:** the wave travels along $\vec{E} \times \vec{B}$. Check options with $\vec{E} \cdot \vec{B} = 0$ and the sign of $\vec{E} \times \vec{B}$. Cyclic: $\hat{i} \times \hat{j} = \hat{k}, \hat{j} \times \hat{k} = \hat{i}, \hat{k} \times \hat{i} = \hat{j}$.
- Read the wave equation:** in $\sin(\omega t - kx)$ or $\sin(kx - \omega t)$ the wave goes along +x; in $\sin(\omega t + kx)$ along -x. $v = \omega/k, \lambda = 2\pi/k, \nu = \omega/2\pi$.
- Refractive index from equations:** $n = c/v = ck/\omega$; dielectric constant $K = n^2$ (for $\mu_r = 1$).
- On entering a medium:** frequency stays the same; speed and wavelength decrease by the factor n .
- E and B in phase;** $u_E = u_B$; each contributes half the intensity (ratio 1 : 1).
- rms vs peak:** $E_0 = \sqrt{2} E_{rms}$. Average energy density $= \epsilon_0 E_{rms}^2 = \frac{1}{2}\epsilon_0 E_0^2$.
- Bulb as point source** with efficiency η : $I = \frac{\eta P}{4\pi r^2}$, then $E_0 = \sqrt{\frac{2I}{c\epsilon_0}}, B_0 = E_0/c$.
- Displacement current** in a capacitor = conduction current in the wires (continuity). For ac: $I_d = \omega CV_0 \cos \omega t$; it decreases as frequency decreases.
- Accelerated charges** radiate; charges at rest or in uniform motion do not.

10. **Spectrum order (increasing ν):** radio $\rightarrow$ micro $\rightarrow$ IR $\rightarrow$ visible (R O Y G B I V) $\rightarrow$ UV $\rightarrow$ X $\rightarrow$ γ . Red has the longest visible wavelength; violet the shortest.
11. **Bands to remember:** AM 530–1710 kHz; FM 88–108 MHz; TV 54–890 MHz; visible 400–700 THz (700–400 nm).
12. **Uses:** IR — physiotherapy, remote control, greenhouse effect (“heat waves”); UV — LASIK, water purifiers, absorbed by ozone and glass; microwaves — radar, ovens; X-rays — fractures, crystal structure; γ — cancer treatment.
13. **Photon energy:** $1240/\lambda(\text{nm})$ eV. Visible $\approx$ 1.8–3.1 eV; X-rays $\approx$ keV; γ -rays $\approx$ MeV.
14. **SONAR uses ultrasound**, which is a mechanical wave, not an EM wave.

