Outstanding Guidance for Youth

Chapter 8
Electromagnetic Waves

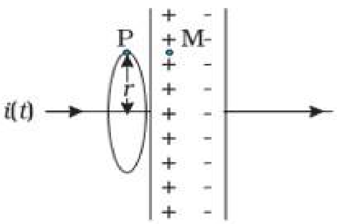
8.1 Introduction

An electrical current produces a magnetic field around it. Further, a magnetic field changing with time gives rise to an electric field. Is the converse also true? Does an electric field changing with time give rise to a magnetic field?

According to James Clerk Maxwell , time-varying electric field generates magnetic field. Maxwell formulated a set of equations involving electric and magnetic fields, known as Maxwell's equations. Maxwell's equations predicted the existence of electromagnetic waves, which are (coupled) timevarying electric and magnetic fields that propagate in space. Hertz, in 1885, experimentally demonstrated the existence of electromagnetic waves. Its technological use by Marconi and others led in due course to the revolution in communication that we are witnessing today.

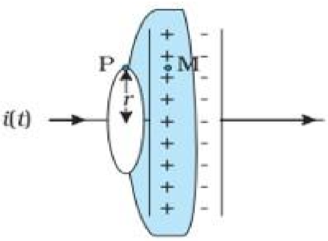
Inconsistency in the Ampere's circuital law and Displacement current

While applying the Ampere's circuital law to find magnetic field at a point outside a capacitor connected to a time-varying current, Maxwell noticed an inconsistency in the Ampere's circuital law.



To find the magnetic field at a point such as P, in a region outside the parallel plate capacitor, consider a plane circular loop of radius r. A current i(t) passes through this surface.

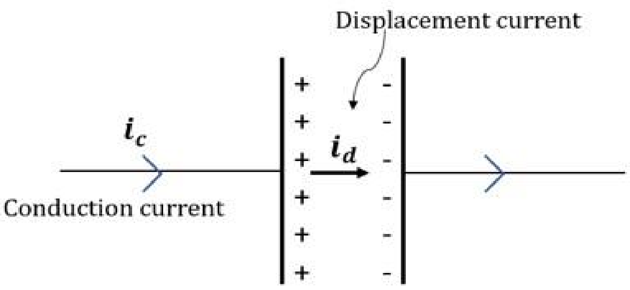
$$\oint B \cdot dl = \mu_0 i(t)$$



To find the magneticfield at the same point P, now consider a pot-shaped surface passing through the interior between the capacitor plates with the same rim as in first case. No current passes through this surface.

$$\oint B \cdot dl = 0 \qquad \text{(This is a contradiction)}$$

To remove this to inconsistency, Maxwell suggested the existence of an additional current , called, the displacement current .



8.2 Displacement Current

The current due to changing electric field or electric flux is called called displacement current or Maxwell's displacement current.

Electric flux $$\phi_E = \frac{q}{s_0}$$

$$\frac{d\phi_E}{dt} = \frac{1}{s_0}\frac{dq}{dt}$$

$$\frac{d\phi_E}{dt} = \frac{1}{s_0} i_d$$

Displacement current $$\mathbf{i_d = \varepsilon_0 \frac{d\phi_E}{dt}}$$

Ampere-Maxwell law

According to Maxwell the source of a magnetic field is not just the conduction electric current due to flowing charges, but also the time rate of change of electric field.

The total current i is the sum of the conduction current (i_c) and displacement current (i_d)

$$i = \mathbf{i_c} + \mathbf{i_d}$$

$$i = i_c + \varepsilon_0 \frac{d\phi_E}{dt}$$

Ampere's theorem become

$$\oint B \cdot dl = \mu_0 (i_C + i_d)$$

$$\oint B \cdot dl = \mu_0 \left(i_c + \varepsilon_0 \frac{d\phi_E}{dt}\right)$$

$$\mathbf{\oint B \cdot dl = \mu_0 i_c + \mu_0 \varepsilon_0 \frac{d\phi_E}{dt}}$$

This is known as Ampere-Maxwell law.

MAXWELL'S EQUATIONS

1. $\oint \mathbf{E} \cdot d\mathbf{A} = Q/\varepsilon_0$ (Gauss's Law for electricity)
2. $\oint \mathbf{B} \cdot d\mathbf{A} = 0$ (Gauss's Law for magnetism)
3. $\oint \mathbf{E} \cdot d\mathbf{l} = \frac{-d\Phi_B}{dt}$ (Faraday's Law)
4. $\oint \mathbf{B} \cdot d\mathbf{l} = \mu_0 i_c + \mu_0 \varepsilon_0 \frac{d\Phi_E}{dt}$ (Ampere – Maxwell Law)

8.3 Electromagnetic waves

Sources of Electromagnetic Waves

- A stationary charge produces only electrostatic fields.
- Charges in uniform motion (steady currents) can produce magnetic fields that, do not vary with time.
- An oscillating charge(accelerating charge) produces an oscillating electric field in space, which produces an oscillating magnetic field, which in turn, is a source of oscillating electric field, and so on. The oscillating electric and magnetic fields thus regenerate each other, as the electro magnetic wave propagates through the space.
  Thus an oscillating charge(accelerating charge) is the source of electromagnetic waves.

An electric charge oscillating harmonically with frequency vv, produces electromagnetic waves of the same frequency vv.

- The experimental demonstration of electromagnetic wave in the radio wave region was done by Hertz in1887.
- Seven years after Hertz, Jagdish Chandra Bose, succeeded in producing and observing electromagnetic waves of much shorter wavelength
  (25 mm to 5 mm).
- At around the same time, Guglielmo Marconi succeeded in transmitting electromagnetic waves over distances of many kilometres. Marconi's experiment marks the beginning of the field of communication using electromagnetic waves.

Nature of Electromagnetic Waves

1) In an e.m waves are transverse waves in which the electric and magnetic fields are perpendicular to each other, and also to the direction of propagation.

2) The speed of e.m.wave in vacuum is,

$$\mathbf{c} = \frac{1}{\sqrt{\mu_0 \varepsilon_0}}$$

3)The speed of of electromagnetic waves in a material medium is
The speed of of electromagnetic waves in a material medium is

$$\mathbf{v} = \frac{1}{\sqrt{\mu \varepsilon}} \quad \text{or} \quad \mathbf{v} = \frac{1}{\sqrt{\mu_0 \mu_r \varepsilon_0 \varepsilon_r}} \quad \text{or} \quad \mathbf{v} = \frac{c}{\sqrt{\mu_r \varepsilon_r}}$$

4) The electric and the magnetic fields in an electromagnetic wave are related as

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

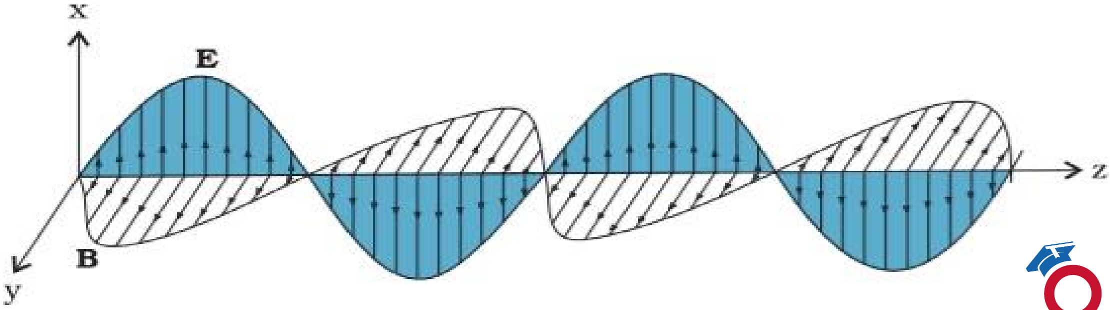
5) No material medium is required for the propagation of e.m.wave.
6) Electromagnetic waves carry energy as they travel through space and this energy is shared equally by the electric and magnetic fields.

7)Electromagnetic waves transport momentum as well. When these waves strike a surface, total momentum delivered to this surface is,

$$p = \frac{U}{c}$$, where U is the energy

Expression for electric field and magnetic field

Consider an electromagnetic wave propagating along the z direction. Let the electric field E_x is along the x-axis and the magnetic field B_y is along the y-axis. Then



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

Here $k = \frac{2\pi}{\lambda}$

k is the propagation constant

$$\omega = 2\pi v$$

ω is the angular frequency

$$\frac{\omega}{k} = \frac{2\pi v}{\frac{2\pi}{\lambda}} = v\lambda = c$$

Speed, $c = \frac{\omega}{k}$

Example

A plane electromagnetic wave of frequency 25 MHz travels in free space along the x-direction. At a particular point in space and time, E = 6.3ĵ V/m. What is B at this point?

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

$$B_0 = \frac{E_0}{c} = \frac{6.3}{3 \times 10^8} = 2.1 \times 10^{-8}\ T$$

E is along y-direction and the wave propagates along x-axis. Therefore, B should be in a direction perpendicular to both x- and y-axes. i.e., B is along z-axis.

Example

The magnetic field in a plane electromagnetic wave is given by
$B_y = 2 \times 10^{-7} \sin(0.5 \times 10^3 x + 1.5 \times 10^{11}\ t)$ T.
a) What is the wavelength and frequency of the wave?
b) Write an expression for the electric field.

(a) $B_y = 2 \times 10^{-7} \sin(0.5 \times 10^3 x + 1.5 \times 10^{11}\ t)$

Comparing with general expression for magnetic field of an em wave travelling in x direction,

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

$$k = 0.5 \times 10^3$$

$$k = \frac{2\pi}{\lambda} = 0.5 \times 10^3$$

$$\lambda = \frac{2\pi}{0.5 \times 10^3}$$

$$= 12.56 \times 10^{-3}\ \text{m}$$

$$\omega = 1.5 \times 10^{11}$$

$$\omega = 2\pi v = 1.5 \times 10^{11}$$

$$v = \frac{1.5 \times 10^{11}}{2\pi}$$

$$= 0.24\ \text{x}10^{11}\ \text{Hz}$$

b) B is along y-direction and the wave propagates along x-axis. Therefore, E should be in a direction perpendicular to both x- and y-axes. i.e., E is along z-axis.

So expression for electric field is ,

$$E_z = E_0 \sin(k\,x - \omega t)$$

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

$$E_0 = B_0\ x\ c$$

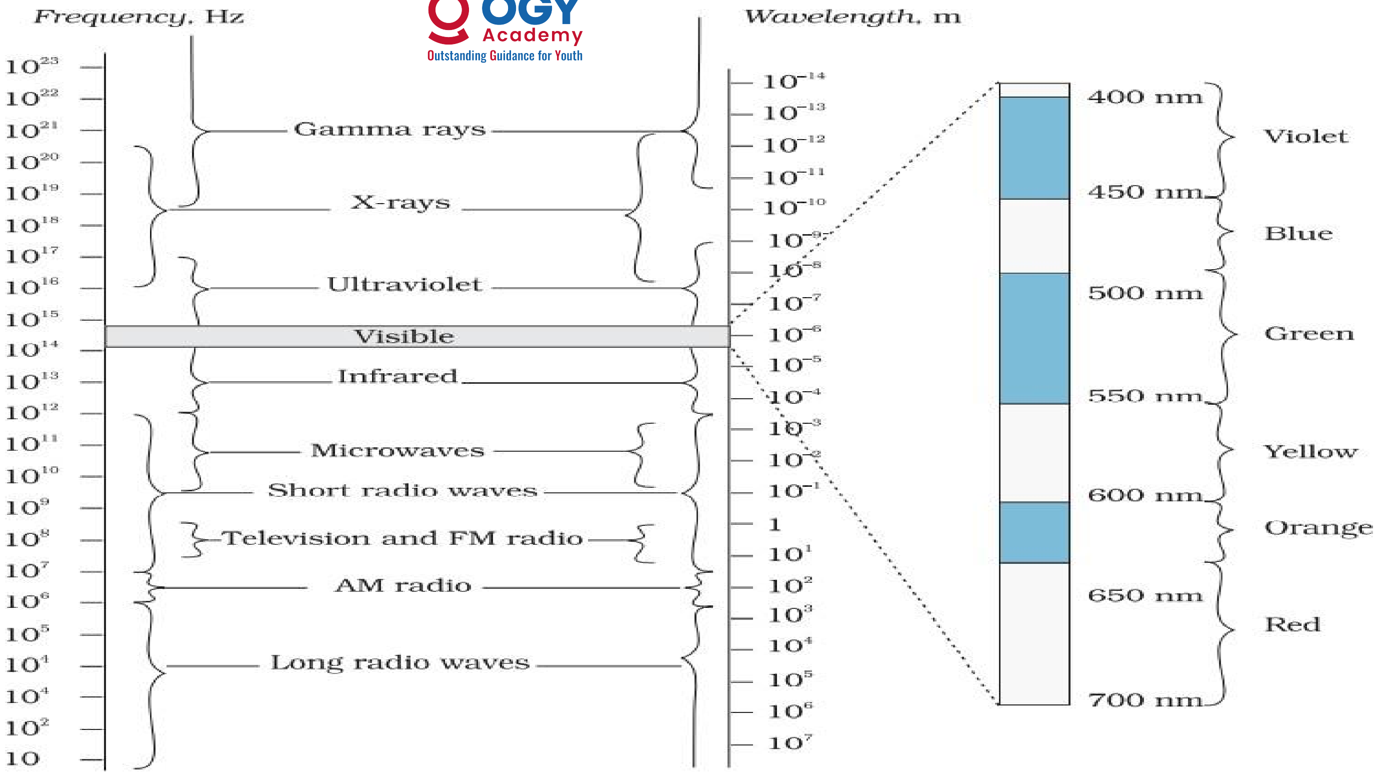
$$= 2 \times 10^{-7}\ \text{x}\ 3 \times 10^8$$

$$= 60\ \text{V/m}$$

$$\mathbf{E_z} = 60 \sin(0.5 \times \mathbf{10^3 x} + 1.5 \times \mathbf{10^{11}}\ t)\ \text{V/m}$$

8.4 Electromagnetic Spectrum

The classification of em waves according to frequency is the electromagnetic spectrum. There is no sharp division between one kind of wave and the next.



Radio waves

- Radio waves are produced by the accelerated motion of charges in conducting wires.
- Frequency range from 500 kHz to about 1000 MHz.
- (i)They are used in radio and television communication systems.
  (ii)Cellular phones use radio waves.

> The AM (amplitude modulated) band 530 kHz - 1710 kHz.
> Short wave bands -frequencies upto 54 MHz .
> TV waves - 54 MHz - 890 MHz.
> The FM (frequency modulated) radio band - 88 MHz - 108 MHz.
> Cellular phones - ultrahigh frequency (UHF) band.

Microwaves

- Microwaves (short-wavelength radio waves), are produced by special vacuum tubes called, klystrons, magnetrons and Gunn diodes.
- Frequencies in the gigahertz (GHz) range,
- (i)Used for radar systems used in aircraft navigation .
  (ii)Used in speed guns used to time fast balls, tennisserves, and automobiles.
  (iii) Microwaves are used in microwave ovens , for cooking.

How is food cooked in microwave ovens?

In microwave ovens, the frequency of the microwaves is selected to match the resonant frequency of water molecules so that energy from the waves is transferred efficiently to the kinetic energy of the molecules. This raises the temperature of any food containing water.

Infrared waves

- Infrared waves are produced by hot bodies and molecules.
- (i) Infrared lamps are used in physical therapy.
  (ii) Infrared radiation plays an important role in maintaining the earth's warmth or average temperature through the greenhouse effect.
  (iii) Infrared detectors are used in Earth satellites, both for military purposes and to observe growth of crops.
  (iv) LEDs emit infrared waves, which are used in the remote switches of TV sets, video recorders and hi-fi systems.

Why IR waves are called heat waves?

Infrared waves are sometimes referred to as heat waves. This is because water molecules present in most materials readily absorb infrared waves
(CO_2, NH_3, also absorb infrared waves). After absorption, their thermal motion increases, that is, they heat up and heat their surroundings.

Greenhouse Effect

Incoming visible light is absorbed by the earth's surface and reradiated as infrared (longer wavelength) radiations. This radiation is trapped by greenhouse gases such as carbon dioxide and water vapour. This trapped Infrared radiation maintains the earth's warmth.

Visible rays

- Electrons in atoms emit The eye light when they move from Photocells one energy level to a Photographic film lower energy level'
- Frequency range of 4×10^{14} Hz to 7×10^{14} Hz
  Wavelength range of about 700 – 400 nm.

Our eyes are sensitive to this range of wavelengths. Different animals are sensitive to different range of wavelengths. For example, snakes can detect infrared waves, and the 'visible' range of many insects extends well into the utraviolet.

Ultraviolet rays

- Ultraviolet (UV) radiation is produced by special lamps and very hot bodies. The sun is an important source of ultraviolet light.
- Wavelength range of (400 nm) to (0.6 nm).
- (i)UV radiations are used in LASIK (Laser assisted in situ keratomileusis) eye surgery.
  (ii) UV lamps are used to kill germs in water purifiers.

Why is depletion of ozone layer , a matter of international concern?

Most of the UV rays from sun is absorbed in the ozone layer in the atmosphere at an altitude of about 40 – 50 km. UV light in large quantities has harmful effects on humans. Exposure to UV radiation induces the production of more melanin, causing tanning of the skin. Ozone layer in the atmosphere plays a protective role, and hence its depletion by chlorofluoro- carbons (CFCs) gas (such as freon) is a matter of international concern.

UV radiation is absorbed by ordinary glass. Hence, one cannot get tanned or sunburn through glass windows. Welders wear special glass goggles or face masks with glass windows to protect their eyes from large amount of UV produced by welding arcs.

X-rays

- One common way to generate X-rays is to bombard a metal target by high energy electrons.
- Wavelengths from about (10 nm) to (10^{-4} nm).
- X-rays are used as a diagnostic tool in medicine and as a treatment for certain forms of cancer.

As X-rays damage or destroy living tissues and organisms, care must be taken to avoid unnecessary or over exposure.

Gamma rays

- This high frequency radiation is produced in nuclear reactions and also emitted by radioactive nuclei.
- Gamma rays are the highest frequency range of the electromagnetic spectrum and have wavelengths of from about 10^{-10}m to 10^{-14}m.
- They are used 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 and decelerations of electrons in aerials	Receiver's aerials
Microwave	0.1m to 1 mm	Klystron valve or magnetron valve	Point contact diodes
Infra-red	1mm to 700 nm	Vibration of atoms and molecules	Thermopiles Bolometer, Infrared photographic film
Light	700 nm to 400 nm	Electrons in atoms emit light when they move from one energy level to a lower energy level	The eye Photocells Photographic film
Ultraviolet	400 nm to 1nm	Inner shell electrons in atoms moving from one energy level to a lower level	Photocells Photographic film
X-rays	1nm 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	-do-