ELECTROMAGNETIC WAVES

Electromagnetic Spectrum

Electromagnetic spectrum. All the known radiations form a big family of electromagnetic waves which stretch over a large range of wavelengths. *The orderly distribution of the electromagnetic waves in accordance with their wavelength or frequency into distinct groups having widely differing properties is called electromagnetic spectrum.*

Electromagnetic wave

An electromagnetic wave is a wave radiated by an accelerated charge and which propagates through space as coupled electric and magnetic fields, oscillating perpendicular to each other and to the direction of propagation of the wave.

Table 8.3 The electromagnetic spectrum

Name	Frequency range (Hz)	Wavelength range	Production	Detection	Main properties and uses
Radiowaves	10^4 to 10^8	> 0.1 m	Rapid acceleration and deaccelerations of electrons in aerials.	Receivers aerials.	Different wavelengths find specialised uses in radio communication.
Microwaves	10^9 to 10^{12}	0.1 m to 1 mm	Klystron valve or magnetron valve.	Point contact diodes.	(*a*) Radar communication. (*b*) Analysis of fine details of molecular and atomic structure. (*c*) Since $\lambda = 3 \times 10^{-2}$ m, useful for demonstration of all wave properties on macroscopic scale.
Infrared	10^{11} to 5×10^{14}	1 mm to 700 nm	Vibration of atoms and molecules.	Thermopiles Bolometer Infrared photographic film.	(*a*) Useful for elucidating molecular structure. (*b*) Less scattered than visible light by atmospheric particles–useful for haze photography.
Visible light	4×10^{14} to 7×10^{14}	700 nm to 400 nm	Electrons in atoms emit light when they move from one energy level to a lower energy level.	Human eye Photocells Photographic film.	(*a*) Detected by stimulating nerve endings of human retina. (*b*) Can cause chemical reaction.
Ultraviolet	10^{16} to 10^{17}	400 nm to 1 nm	Inner shell electrons in atoms moving from one energy level to a lower level.	Photocells Photographic film.	(*a*) Absorbed by glass (*b*) Can cause many chemical reactions, *e.g.*, the tanning of the human skin. (*c*) Ionize atoms in atmosphere, resulting in the ionosphere.
X-rays	10^{16} to 10^{19}	1 nm to 10^{-3} nm	X-ray tubes or inner shell electrons.	Photographic film, Geiger tubes, Ionization chamber.	(*a*) Penetrate matter (*e.g.*, radiography) (*b*) Ionize gases (*c*) Cause fluorescence (*d*) Cause photoelectric emission from metals. (*e*) Reflected and diffracted by crystals enabling ionic lattice spacing and N_A (or wave-length) to be measured.
Gamma rays	10^{18} to 10^{22}	< 10^{-3} nm	Radioactive decay of the nucleus.	Photographic film, Geiger tubes, Ionization chamber.	Similar to X-rays.

1. Radio waves. These are the e.m. waves of longest wavelength and minimum frequency.

Wavelength range	600 m to 0.1 m
Frequency range	500 kHz to 1000 MHz
Source	Accelerated motion of charges in conducting wires or oscillating circuits.
Discovered by	Marconi in 1895
Properties	Reflection, diffraction

Uses of radio waves :

(*i*) In radio and television communication systems.

(*ii*) In radioastronomy.

2. Microwaves. They are the e.m. waves having wavelengths next smaller to radiowaves.

Wavelength range	0.3 m to 10^{-3} m
Frequency range	10^9 Hz to 10^{12} Hz
Source	Oscillating currents in special vacuum tubes like klystrons, magnetrons and Gunn diodes.
Discovered by	Marconi in 1895
Properties	Reflection, refraction, diffraction and polarisation. Due to their shorter wavelengths, they can travel as a beam in a signal.

Uses of microwaves :

(*i*) In radar systems for aircraft navigation.

(*ii*) In long-distance communication systems via geostationary satellites.

(*iii*) In microwave ovens.

3. Infrared waves. These radiations lie close to the low-frequency or long-wavelength of the visible spectrum. Infrared waves produce heating effect, so they are also known as ***heat waves*** or ***thermal radiation***.

The water molecules (and also CO_2, NH_3 molecules) present in different materials readily absorb infrared waves, increase the thermal motions and hence heat up the materials and their surroundings.

Wavelength range	5×10^{-3} m to 10^{-6} m
Frequency range	10^{11} Hz to 5×10^{14} Hz
Source	Hot bodies and molecules.
Discovered by	William Herschel in 1800.
Properties	Heating effect, reflection, refraction, diffraction and propagation through fog.

Uses of Infrared waves :

(*i*) In the remote control of a TV or VCR, the keypad of which contains a small infrared transmitter.

(*ii*) In green houses to keep the plants warm.

(*iii*) In haze photography because infrared waves are less scattered than visible light by atmospheric particles.

(*iv*) Infrared lamps in the treatment of muscular complaints.

(*v*) In reading the secret writings on the ancient walls.

(*vi*) In knowing the molecular structure.

4. Visible light. It is a very small part of the e.m. spectrum towards which the human retina is sensitive. The visible light emitted or reflected from bodies around us gives information about the world.

Wavelength range	8×10^{-7} m to 4×10^{-7} m.
Frequency range	4×10^{14} Hz to 7×10^{14} Hz
Source	Radiated by excited atoms in ionised gas and incandescent bodies.
Properties	Reflection, refraction, interference, diffraction, polarisation, photoelectric effect, photographic action, sensation of sight.

Uses of visible light :

(*i*) It provides us the information of the world around us.

(*ii*) It can cause chemical reactions.

The approximate wavelength ranges for lights of different colours are as follows :

5. Ultraviolet light. This region of the e.m. spectrum has wavelengths just shorter than visible light and can be detected just beyond the violet end of the solar spectrum.

Wavelength range	3.5×10^{-7} m to 1.5×10^{-7} m
Frequency range	10^{16} Hz to 10^{17} Hz
Source	High voltage gas discharge tubes, arcs of iron and mercury, the sun
Discovered by	Ritter in 1800
Properties	Effect on photographic plate, fluorescence, ionisation, highly energetic, tanning of the human skin.

Uses of ultraviolet light :

(*i*) In food preservation.

(*ii*) In the study of invisible writings, forged documents and finger prints.

(*iii*) In the study of molecular structure.

The ultraviolet light in large quantities has harmful effects on human beings. But fortunately, most of the ultraviolet light coming from the sun is absorbed by the ozone layer in the atomosphere at an altitude of about 40 – 50 km.

6. X-rays. These e.m. waves have wavelengths just shorter than ultraviolet light. As X-rays can pass through many forms of matter, so they have many useful medical and industrial applications.

Wavelength range	100 Å to 0.1 Å
Frequency range	10^{18} Hz to 10^{20} Hz
Source	Sudden deceleration of fast moving electrons by a metal target.
Discovered by	Rontgen in 1895
Properties	Effect on photographic plate, ionisation of gases, photoelectric effect, fluorescence, more energetic than UV rays.

Uses of X-rays :

(*i*) In medical diagnosis because X-rays can pass through flesh but not through bones.

(*ii*) In the study of crystals structure because X-rays can be reflected and diffracted by crystals.

(*iii*) In *engineering* for detecting faults, cracks, flaws and holes in the finished metal products.

(*iv*) In *detective departments* to detect explosives, diamond, gold, etc. in the possession of smugglers.

(*v*) In radiotherapy to cure untracable skin diseases and malignant growths.

7. Gamma rays. These are e.m. radiations of highest frequency range and lowest wavelength range. These are most penerating e.m. waves.

Wavelength range	10^{-14} m to 10^{-10} m.
Frequency range	10^{18} Hz to 10^{22} Hz.
Source	Radioactive nuclei and nuclear reactions. Co - 60 is a pure γ-ray source.
Discovered by	Henry Becquerel in 1896
Properties	Effect on photographic plate, fluorescence, ionisation, diffraction, high penetrating power.

Uses of γ-rays :

(*i*) In radiotherapy for the treatment of malignant tumours.

(*ii*) In the manufacture of polyethylene from ethylene.

(*iii*) To initiate some nuclear reactions.

(*iv*) To preserve food stuffs for a long time because soft γ-rays can kill micro-organisms.

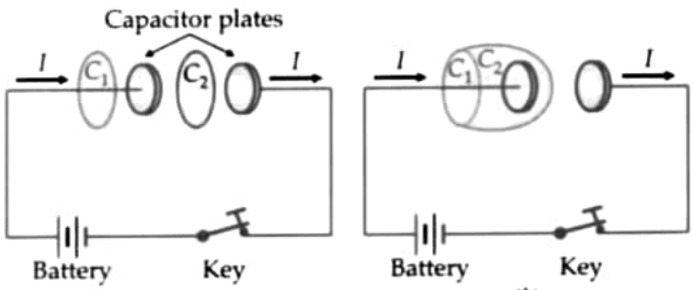
(*v*) To study the structure of atomic nuclei.

Maxwell Displacement Current

Inconsistency of Ampere's circuital law:- According to Ampere's circuital law, the line integral of the magnetic field $\vec{B}$ *along any closed loop C is proportional to the current I passing through the closed loop, i.e.,*

$$\oint_C \vec{B}.\vec{dl} = \mu_0 I \quad ...(1)$$

In 1864, Maxwell showed that the equation (1) is logically inconsistent. To prove this inconsistency, we consider a parallel plate capacitor being charged by a battery as shown in Fig. 8.1(*a*). As the charging



(*a*) (*b*)

continues, a current *I* flows through the connecting wires, which of course changes with time. This current produces a magnetic field around the capacitor. Consider two planar loops C_1 and C_2, C_1 just left of the capacitor and C_2 in between the capacitor plates, with their planes parallel to these plates.

Now the current *I* flows across the area bounded by loop C_1 because connecting wire passes through it. Hence from Ampere's law, we have

$$\oint_{C_1} \vec{B}.\vec{dl} = \mu_0 I \quad ...(2)$$

But the area bounded by C_2 lies in the region between the capacitor plates, so no current flows across it.

$$\therefore \quad \oint_{C_2} \vec{B}.\vec{dl} = 0 \quad ...(3)$$

Imagine the loops C_1 and C_2 to be infinitesimally close to each other, as shown in Fig. 8.1(*b*). Then we must have

$$\oint_{C_1} \vec{B}.\vec{dl} = \oint_{C_2} \vec{B}.\vec{dl} \quad ...(4)$$

This result is inconsistent with the equations (2) and (3). So a need for modifying Ampere's law was felt by Maxwell.

Maxwell's modification of Ampere's law : Displacement current. To modify Ampere's law, Maxwell followed a symmetry consideration. By Faraday's law, a changing magnetic field induces an electric field, hence a changing electric field must induce a magnetic field. As currents are the usual sources of magnetic fields, a changing electric field must be associated with a current. Maxwell called this current as the *displacement current* to distinguish it from the usual conduction current caused by the drift of electrons.

Displacement current *is that current which comes into existence, in addition to the conduction current, whenever the electric field and hence the electric flux changes with time.*

To maintain the dimensional consistency, the displacement current is given the form :

$$I_d = \varepsilon_0 \frac{d\phi_E}{dt}$$

where ϕ_E = electric field × area = EA, is the electric flux across the loop.

∴ Total current across the closed loop

$$= I_c + I_d = I_c + \varepsilon_0 \frac{d\phi_E}{dt}$$

Hence the modified form of the Ampere's law is

$$\oint \vec{B} \cdot \vec{dl} = \mu_0 \left[I_c + \varepsilon_0 \frac{d\phi_E}{dt} \right] \qquad ...(5)$$

Unlike the conduction current, the displacement current exists whenever the electric field and hence the electric flux is changing with time. Thus according to Maxwell, the source of a magnetic field is not just the conduction electric current due to flowing charges, but also the time-varying electric field. Hence the total current I is the sum of the conduction current I_c and displacement current I_d

$$I = I_c + I_d = I_c + \varepsilon_0 \frac{d\phi_E}{dt}$$

Important properties of displacement current. These are as follows :

1. Displacement current exists whenever there is a change of electric flux. Unlike conduction current, it does not exist under steady conditions.
2. It is not a current. It only adds to current density in Ampere's circuital law. As it produces magnetic field, so it is called a current.
3. The magnitude of displacement current is equal to the rate of displacement of charge from one capacitor plate to the other.
4. Together with the conduction current, displacement current satisfies the property of continuity.

Electromagnetic wave

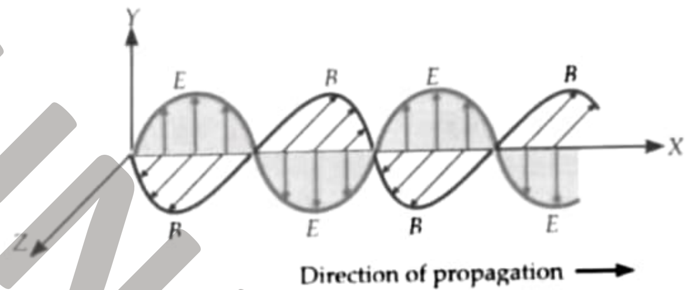
A time-varying magnetic field is a source of changing electric field.

A time-varying electric field is a source of changing magnetic field.

Transverse nature of Electromagnetic wave :-

An electromagnetic wave is a wave radiated by an accelerated charge and which propagates through space as coupled electric and magnetic fields, oscillating perpendicular to each other and to the direction of propagation of the wave.

Figure 8.5 shows a plane electromagnetic wave travelling along X-axis. The electric field $\vec{E}$ oscillates along Y-axis while the magnetic field $\vec{B}$ oscillates along Z-axis.



The directions of oscillations of $\vec{E}$ and $\vec{B}$ fields are perpendicular to each other as well as perpendicular to the direction of propagation of the wave. So the electromagnetic waves are transverse in nature.

Mathematical expression :-

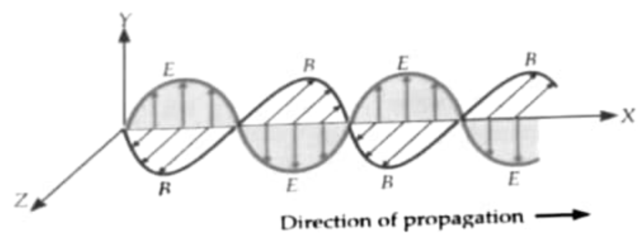


Fig. 8.5 A plane electromagnetic wave travelling along X-axis.

The values of electric and magnetic fields shown in the above figure depend only on x and t. The electric field vector can be represented mathematically as follows :

$$\vec{E} = E_y\,\hat{j} = E_0 \sin(kx - \omega t)\,\hat{j}$$

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

$$= E_0 \sin\left[2\pi\left(\frac{x}{\lambda} - \frac{t}{T}\right)\right]\hat{j} \qquad \text{...(1)}$$

where $k = 2\pi/\lambda$ is the propagation constant of the wave and angular frequency, $\omega = 2\pi\nu$.

Clearly, $E_x = E_z = 0$

The magnetic field vector may be represented as

$$\vec{B} = B_z\,\hat{k} = B_0 \sin(kx - \omega t)\,\hat{k}$$

$$= B_0 \sin\left[2\pi\left(\frac{x}{\lambda} - \nu t\right)\right]\hat{k}$$

$$= B_0 \sin\left[2\pi\left(\frac{x}{\lambda} - \frac{t}{T}\right)\right]\hat{k} \qquad \text{...(2)}$$

Clearly, $B_x = B_y = 0$.

Here E_0 and B_0 are the *amplitudes* of the electric field $\vec{E}$ and magnetic field $\vec{B}$, respectively.

Equations (1) and (2) show that the *variations in electric and magnetic fields are in same phase, i.e.*, both attain their maxima and minima at the same instant and at the same place (x).

The magnitudes of $\vec{E}$ and $\vec{B}$ are related as

$$\frac{E}{B} = c \quad \text{or} \quad \frac{E_0}{B_0} = c$$

Maxwell also showed that the speed of an e.m. wave depends on the permeability and permittivity of the medium through which it travels. The speed of an e.m. wave in free space is given by

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

Permeability of free space,

$$\mu_0 = 4\pi \times 10^{-7}\ \text{Ns}^2\,\text{C}^{-2}$$

Permittivity of free space,

$$\varepsilon_0 = 8.85 \times 10^{-12}\ \text{C}^2\text{N}^{-1}\text{m}^{-2}$$

$$\therefore \quad c = \frac{1}{\sqrt{4\pi \times 10^{-7} \times 8.85 \times 10^{-12}}}$$

$$= \mathbf{3.0 \times 10^8\ ms^{-1}}$$

which is the speed of light in vacuum. This fact led

Properties of electromagnetic wave

1. The electromagnetic waves are produced by accelerated charges and do not require any material medium for their propagation.
2. The directions of oscillations of $\vec{E}$ and $\vec{B}$ fields are perpendicular to each other as well as perpendicular to the direction of propagation of the wave. So the electromagnetic waves are transverse in nature.
3. The oscillations of $\vec{E}$ and $\vec{B}$ fields are in same phase.
4. All electromagnetic waves travel in free space with the same speed,

   $$c = \frac{1}{\sqrt{\mu_0 \varepsilon_0}} = 3 \times 10^8\ \text{ms}^{-1}$$

   In a material medium, the electromagnetic waves travel with the speed,

   $$v = \frac{1}{\sqrt{\mu\varepsilon}} = \frac{c}{\sqrt{\mu_r \varepsilon_r}} = \frac{c}{n}$$

   where n is the refractive index of the medium.
5. The amplitude ratio of the electric and magnetic fields is $\dfrac{E_0}{B_0} = c = \dfrac{1}{\sqrt{\mu_0 \varepsilon_0}}$
6. The electromagnetic waves carry energy as they travel through space and this energy is shared equally by the electric and magnetic fields. The average energy density of an e.m. wave is

   $$u = u_E + u_B = \frac{1}{2}\left[\varepsilon_0 E_0^2 + \frac{B_0^2}{\mu_0}\right]$$

7. Electromagnetic waves transport linear momentum as they travel through space :

   $$p = \frac{U}{c}.$$

8. Electromagnetic waves are not deflected by electric and magnetic fields.
9. Electromagnetic waves obey the principle of superposition. They show the properties of reflection, refraction, interference, diffraction and polarisation.
10. The electric field of an electromagnetic wave is responsible for its optical effects, because $E_0 >> B_0$.