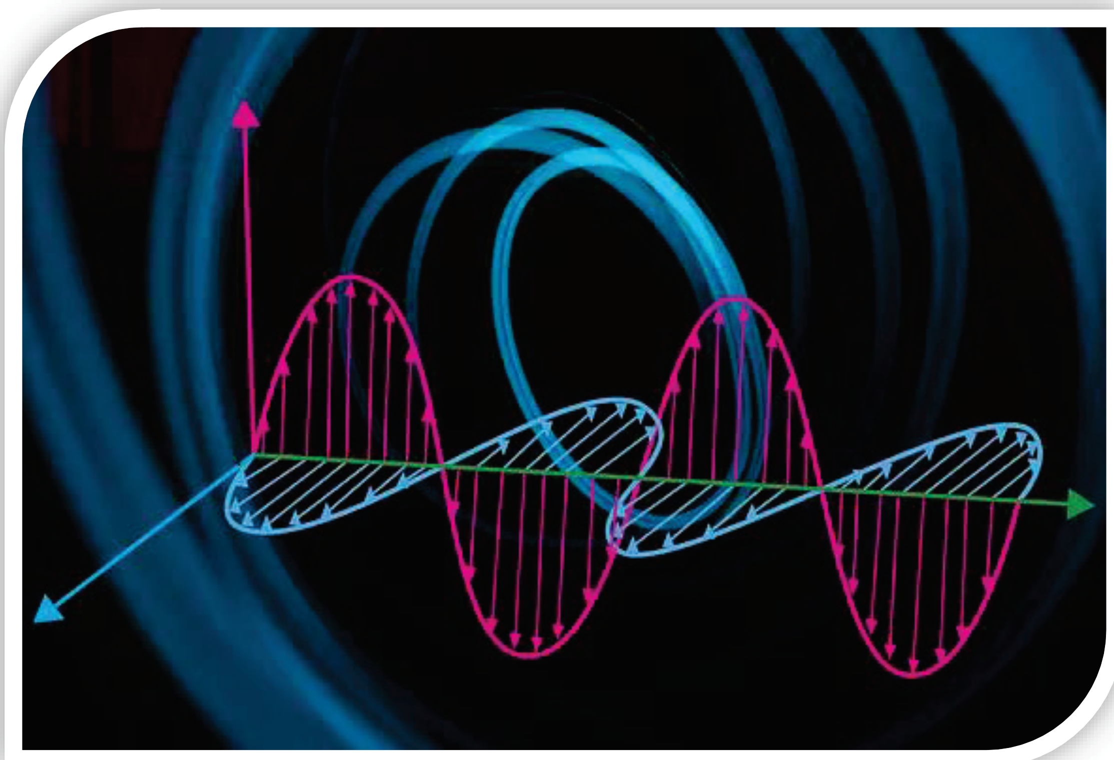
Electromagnetic Waves



Electromagnetic Waves

Electric and magnetic phenomena are not totally independent, but are related to each other. By the middle of the nineteenth century, several empirical laws of electricity and magnetism had been established. However, there was no convincing theoretical explanation for these phenomena. A comprehensive theory which could explain all the electric and magnetic phenomena was developed by James Clerk Maxwell around 1872. This theory is referred to as the 'electromagnetic theory'. Maxwell unified not only the apparently distinct theories on electricity and magnetism but also showed that light is electromagnetic in nature.

Maxwell's equations

1. $\oint E \cdot dS = \frac{q}{\varepsilon_0}$: Gauss' law in electrostatics
2. $\oint \vec{B} \cdot \vec{dS} = 0$ L Gauss's law in magnetism.
3. $\oint \vec{E} \cdot \vec{dl} = -\frac{dQ_B}{dt}$: Faraday's law of electromagnetic induction
4. $\oint \vec{E} \cdot \vec{dl} = \mu_0 (I_c + I_d)$: Ampere-Maxwell law.

Displacement current

The term I_d in the fourth equation is called displacement current. $I_d = \varepsilon_0 \frac{d\phi_E}{dt}$

Displacement current through a charging capacitor, $I_d = C\frac{dV}{dt}$

Electromagnetic waves

Electromagnetic waves consists of oscillating electric and magnetic fields. These fields oscillate in perpendicular directions, perpendicular to the direction of propagation. In a plane electromagnetic wave, travelling along z direction the oscillations of the electric and magnetic fields are represented as

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

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

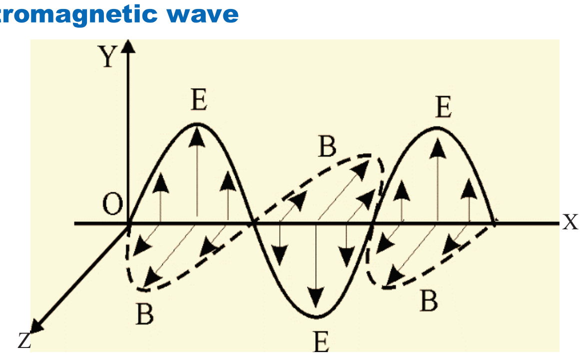
Here $k = \frac{2\pi}{\lambda}$; $\omega = 2\pi f$; $\frac{\omega}{K} = c$, the speed of propagation of the waves. It can be shown that $c = \frac{1}{\sqrt{\mu_0 \varepsilon_0}}$. Also $c = \frac{E_0}{B_0}$

(a) The intensity of electromagnetic wave is given by $I = \frac{1}{2}\varepsilon_0 E_0^2 c = \frac{1}{2\mu_0} B_0^2 c$

(b) The average energy density of electromagnetic wave is given by $U_{av} = \frac{1}{2}\varepsilon_0 E_0^2 = \frac{1}{2\mu_0} B_0^2$

(c) The momentum transferred by an electromagnetic wave on t an absorbing surface is given by $p = \frac{I}{c}$.

Properties of electromagnetic wave



Electromagnetic wave

1. Electromagnetic waves propagate in the form of time varying electric and magnetic fields such that the two fields are perpendicular to each other and also to the direction of propagation of the waves (Figure). In other words, electromagnetic waves are transverse in nature.
2. Electromagnetic waves are produced by accelerated charges
3. Electromagnetic waves travel in free space (or vacuum) with a speed c given by

$$c = \frac{1}{\sqrt{\mu_0 \epsilon_0}} = 3\times10^8\,\text{m s}^{-1} \qquad \ldots (1)$$

μ_0 and ϵ_0 being the permeability and permittivity of free space which have values $4\pi \times 10^{-7}$ H m^{-1} and 8.85×10^{-12} F m^{-1}. The electromagnetic waves travel in a material medium of absolute permittivity ε and absolute permeability μ with a speed v given by $v = \frac{1}{\sqrt{\mu\varepsilon}}$ … (2)

4. Electromagnetic waves do not need any material medium for their propagation.
5. The ratio of the amplitudes of electric and magnetic fields is always a constant and it is equal to the velocity of electromagnetic waves.

Mathematically, $\frac{E_0}{B_0} = c$ … (3)

6. The energy of electromagnetic waves is equally divided between the electric and magnetic field vectors.
7. The direction of flow of electromagnetic wave is given by the direction of a vector, called Poynting's vector $(\vec{S})$. The magnitude of $\vec{S}$ gives the amount of energy flowing normally across unit area $\vec{S} = \frac{\vec{E}\times\vec{B}}{\mu_0}$

Electromagnetic spectrum

The orderly distribution of electromagnetic waves (according to wavelength or frequency) in the form of distinct groups, having widely different properties, is called electromagnetic spectrum. The spectrum of electromagnetic radiation has a wide range of wavelengths from radio-waves at one end to γ-rays at the other end. The spectrum from about 400 nm to 700 nm which is sensitive to human eye is called the visible spectrum. The spectrum is divided into various regions depending on the effects produced by them. A sequence of regions in the decreasing order of wavelengths is; radio waves, microwaves, infra-red rays, visible light, ultraviolet rays, X-rays and γ-rays.

Table below gives details about the frequency range, mode of production and use of different types of electromagnetic waves in the order of decreasing wavelength.

Electromagnetic spectrum

	Name	Frequency range (Hz)	Mode of production	Uses
1	Radio waves	3×10^4 to 3×10^9	By accelerated motion of charges in conducting wires	Radio and TV communication, cellular phones in the UHF band
2.	Micro waves	3×10^9 to 3×10^{11}	Klystrons tubes, Magnetron tubes	Radar systems, Microwave ovens
3.	Infrared waves	3×10^{11} to 4×10^{14}	Hot bodies and molecules	Infrared lamps for physical therapy, For weather forecasting, to study the molecular structure and to check purity of the chemical samples, IR photography
4.	Visible light	4×10^{14} to 8×10^{14}	Emitted or reflected from objects around us	Information about the world around us
5.	UV rays	8×10^{14} to 5×10^{17}	Spectral lamps and very hot bodies	Molecular structure studies through UV spectra, Burglar alarm, to preserve food stuff
6.	X-rays	5×10^{17} to 3×10^{21}	By bombarding a metal target by high energy electrons	In medical applications, surgery, Radio therapy, industry and scientific research
7.	γ-rays	Above 3×10^{18} to 5 up to 10^{23}	Nuclear reactions and Radioactive nuclei	Treatment of cancer and tumours, preservation of food, in nuclear reactions, structure of atomic nucleus

Illustrations

1. One requires 11 eV of energy to dissociate a carbon monoxide molecule into carbon and oxygen atoms. The minimum frequency of the appropriate electromagnetic radiation to achieve the dissociation lies in

(A) Visible region.
(B) Infrared region.
(C) Ultraviolet region.
(D) Microwave region.

Ans (C

$$E\text{ (in eV)} = \frac{hc}{e\lambda} \simeq \frac{1242}{\lambda(\text{nm})}$$

$$\lambda(\text{in nm}) = \frac{1242}{11} \simeq 113 \text{ nm}$$

$$\Rightarrow \text{Frequency}, \nu = \frac{3\times10^8}{1.13\times10^{-7}} = 2.65\times10^{15} \text{ Hz}$$

This lies in ultraviolet region

2. A linearly polarized electromagnetic wave given as $E = E_0\hat{i}\cos(kz-\omega t)$ is incident normally on a perfectly reflecting infinite wall at $z = a$. Assuming that the material of the wall is optically inactive, the reflected wave will be given as

(A) $E_r = -E_0\hat{i}\cos(kz-\omega t)$
(B) $E_r = E_0\hat{i}\cos(kz+\omega t)$
(C) $E_r = -E_0\hat{i}\cos(kz+\omega t)$
(D) $E_r = E_0\hat{i}\sin(kz-\omega t)$

Ans (B)

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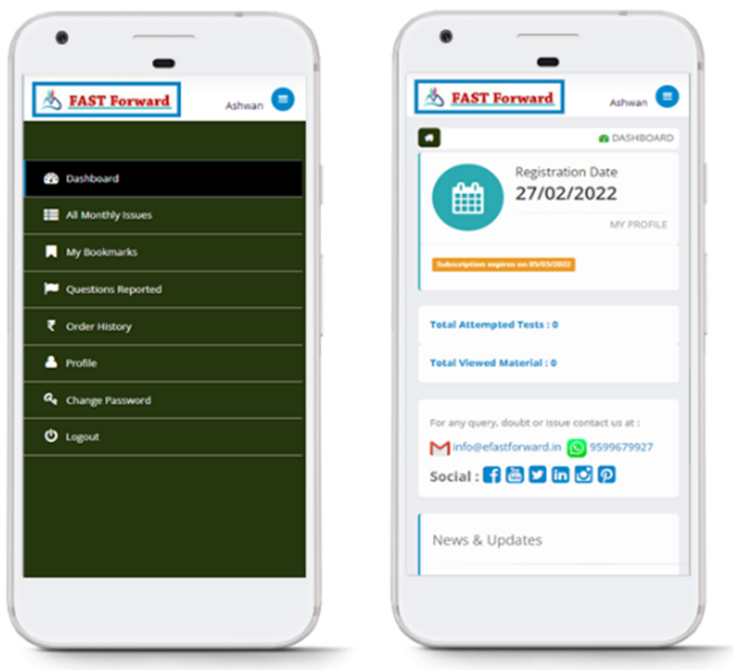

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