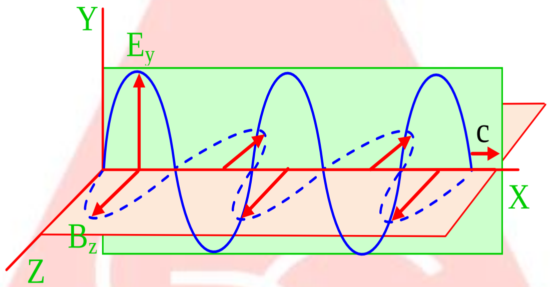
ELECTROMAGNETIC WAVES

1 INTRODUCTION

A changing electric field produces a changing magnetic field and vice versa which gives rise to a transverse wave known as electromagnetic waves. The time varying electric field and magnetic field mutually perpendicular to each other also perpendicular to the direction of propagation.

Thus the electromagnetic waves consist of sinusoidally time varying electric and magnetic field acting at right angles to each other as well as at right angles to the direction of propagation.



2 HISTORY OF ELECTROMAGNETIC WAVES

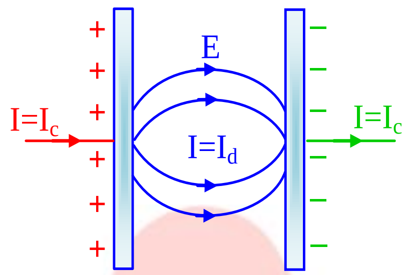
- In the year 1865, Maxwell predicted the electromagnetic waves theoretically. According to him, an accelerated charge sets up a magnetic field in its neighborhood.
- In 1887, Hertz produced and detected electromagnetic waves experimentally at wavelength of about 6m.
- Seven year later, J.C. Bose became successful in producing electromagnetic waves of wavelength in the range 5mm to 25 mm.
- In 1896, Marconi discovered that if one of the spark gap terminals is connected to an antenna and the other terminal is earthed, the electromagnetic waves radiated could go upto several kilometers.
- The antenna and the earth wires from the two plates of a capacitor which radiates radio frequency waves. These waves could be received at a large distance by making use of an antenna earth system as detector.
- Using these arrangements, in 1899 Marconi first established wireless communication across the English channel i.e., across a distance of about 50 km.

3 CONCEPT OF DISPLACEMENT CURRENT

When a capacitor is allowed to charge in an electric circuit, the current flows through connecting wires. As capacitor charges, charge accumulates on the two plates of capacitor and as a result, a changing electric field is produced across between the two plate of the capacitor.

According to Maxwell changing electric field intensity is equivalent to a current through capacitor that current is known as displacement current (I_0). If +q and –q be the charge on the left and right plates of the capacitor respectively at any instant if σ be the surface charge density of plate of capacitor the electric field between the plate is given by

$$E = \frac{\sigma}{\epsilon_0} = \frac{q}{\epsilon_0 A}$$



charge on the plates of the capacitor increased by dq in time dt then dq = I dt

change in electric field is

$$dE = \frac{dq}{\epsilon_0 A} = \frac{Idt}{\epsilon_0 A} \Rightarrow \frac{dE}{dt} = \frac{I}{\epsilon_0 A}$$

$$I = \epsilon_0 A \frac{dE}{dt} = \epsilon_0 \frac{d}{dt}(EA) = \epsilon_0 \frac{d\phi_E}{dt} \quad (\because \phi_E = EA)$$

$$\boxed{I_d = \epsilon_0 \frac{d\phi_E}{dt}}$$

The conduction current is the current due to the flow of charges in a conductor and is denoted as I_c and **displacement current** is the current due to changing electric field between the plate of the capacitor and denoted as I_d so the total current I is sum of I_c and I_d i.e. $I = I_c + I_d$

Ampere's circuital law can be written as

$$\oint \vec{B}.\vec{d\ell} = \mu_0(I_c + I_d) \Rightarrow \oint \vec{B}.\vec{d\ell} = \mu_0\left(I_c + \epsilon_0 \frac{d\phi_E}{dt}\right)$$

4 MAXWELL'S EQUATIONS AND LORENTZ FORCE

The existence of electro-magnetic waves that propagate through the space in the form of varying electric and magnetic fields has been predicted by the four basic laws of electromagnetism which are called **Maxwell's equations.**

(i) Gauss's law in electrostatics% It states that the total electric flux through any closed surface is equal to $\frac{1}{\varepsilon_0}$ times the net charge enclosed by

Mathematically,

$$\oint \vec{E}.\vec{ds} = \frac{q}{\epsilon_0}$$

This equation is called Maxwell's first equation.

(ii) Gauss'law in magnetism% It states that the net magnetic flux crossing any closing surface is always zero.

Mathematically,

$$\oint \vec{B}.\vec{ds} = 0$$

This equation is called Maxwell's second equation. A direct consequence of this equation is that the magnetic monpoles do not exist.

(iii) Faradays's law of electromagnetic induction% It states that the induced emf produced in a circuit is numerically equal to the rate of change of magnetic flux through it.

Mathematically,

$$\varepsilon = -\frac{d\phi_B}{dt}$$

$$\text{emf} = \oint \vec{E}.\vec{d\ell} = -\frac{d\phi_B}{dt}$$

This equation is called Maxwell's third equation.

The negative sign in this equation indicates that the induced emf produced opposes the rate of change of magnetic flux.

(iv) Maxwell-Ampere circuital law% It states that the line integral of magnetic field along a closed path is equal to μ_0 times the total current (i.e., sum of conduction and displacement currents threading the surface bounded by that closed path)

Mathematically, $\oint \vec{B}.\vec{d\ell} = \mu_0\left[I_c + \epsilon_0 \frac{d\phi_E}{dt}\right]$

This equation is called **Maxwell's fourth equation**.

(v) Lorentz: The vector sum of electric force and magnetic force on any charged particle is called the Lorentz force.

$$\vec{F} = q[\vec{E} + (\vec{v} \times \vec{B})]$$

The above five equations give a complete description of all electromagnetic interactions.

SUMMARY:

There are four maxwell's equation are given below

(1) Gauss law in electrostatics : $\oint \vec{E}.\vec{ds} = \frac{q}{\epsilon_0}$ ***....(i)***

(2) Guass law in magnetism : $\oint \vec{B}.\vec{ds} = 0$ ***...(ii)***

(3) Faraday's law of electromagnetic induction :

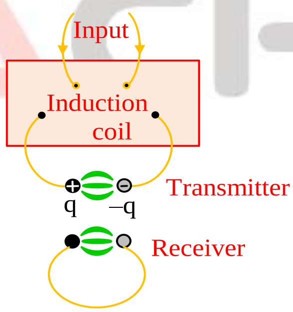
emf = $\oint \vec{E}.\vec{d\ell} = -\frac{d\phi_B}{dt}$ ***...(iii)***

(4) Maxwell - Ampere's circuital law :

$\oint \vec{B}.\vec{d\ell} = \mu_0\left[I_c + \epsilon_0 \frac{d\phi_E}{dt}\right]$ ***....(iv)***

5 HERTZ EXPERIMENT (PRACTICAL PRODUCTION OF EM WAVES)

- In 1888, Hertz demonstrated the production of electromagnetic waves by oscillating charge. His experimental apparatus is shown schematically in figure.



- An induction coil is connected to two spherical electrodes with a narrow gap between them. It acts as a transmitter. The coil provides short voltage surges to the spheres making one positive and the other negative. A spark is generated between the spheres when the voltage between them reaches the breakdown voltage for air. As the air in the gap is ionized, it conducts more rapidly and the discharge between the spheres becomes oscillatory.
- The above experimental arrangement is equivalent to an LC circuit, where the inductance is that of

the loop and the capacitance is due to the spherical electrodes.

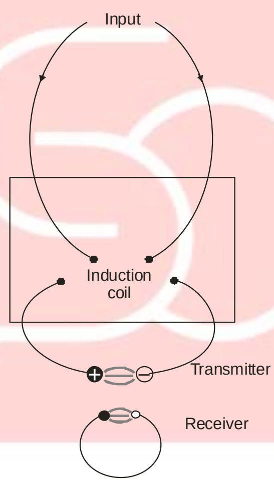
- Electromagnetic waves are radiated at very high frequency ($\approx$ 100 MHz) as a result of oscillation of free charges in the loop.
- Hertz was able to detect these waves using a single loop of wire with its own spark gap (the receiver).
- Sparks were induced across the gap of the receiving electrodes when the frequency of the receiver was adjusted to match that of the transmitter.

6 PRODUCTION OF ELECTROMAGNETIC WAVES

(i) **According to Maxwell**, an accelerated charge sets up a magnetic field in its neighbourhood. The magnetic field, in turn, produces an electric field in that region. Both these fields vary with time and act as sources for each other.

(ii) As oscillating charge is accelerated continuously, it will radiate electromagnetic waves continuously.

(iii) In 1988, Hertz demonstrated the production of electromagnetic apparatus is shown schematically in fig.



(iv) An induction coil is connected to two spherical electrodes with a narrow gap between them. It acts as a transmitter. The coil provides short voltage surges to the spheres making one positive and the other negative. A spark is generated between the spheres when the voltage between them reaches the breakdown voltage for air. As the air in the gap is ionised, it conducts more rapidly and the discharge between the spheres becomes oscillatory.

(v) The above experiment arrangment is equivalent to an LC circuit, where the inductance is that of the loop and the capacitance is due to the spherical electrodes.

(vi) Electromagnetic waves are radiated at very high frequency($\approx$100 MHz) as a result of oscillation of free charges in the loop.

(vii) Hertz was able to detect these waves using a single loop of wire with its own spark gap (the receiver).

(viii) Sparks were induced across the gap of the receiving electrodes when the frequency of the receiver was adjusted to match that of the transmitter.

7 PROPERTIOES OF ELECTROMAGNETIC WAVES

- The electric and magnetic fields satisfy the following wave equations, which can be obtained from Maxwell's third and fourth equations.

$$\frac{\partial^2 E}{\partial x^2} = \mu_0\varepsilon_0 \frac{\partial^2 E}{\partial t^2} \quad \text{and} \quad \frac{\partial^2 B}{\partial x^2} = \mu_0\varepsilon_0 \frac{\partial^2 B}{\partial t^2}$$

- Electromagnetic waves travel through vacuum with the speed of light c, where

$$c = \frac{1}{\sqrt{\mu_0 \varepsilon_0}} = 3 \times 10^8 \text{ m/s}$$

- The electric and magnetic fields of an electromagnetic wave are perpendicular to each other and also perpendicular to the direction of wave propagation. Hence, these are transverse waves.
- The instantaneous magnitudes of $\vec{E}$ and $\vec{B}$ in an electromagnetic wave are related by the expression $\frac{E}{B} = c$
- Electromagnetic waves carry energy. The rate of flow of energy crossing a unit area is described by the Poynting vector $\vec{S}$. Where $\vec{S} = \frac{1}{\mu_0}\vec{E} \times \vec{B}$.
- Electromagnetic waves carry momentum and hence can exert pressure (P) on surfaces, which is known as radiation pressure. For an electromagnetic wave with Poynting vector $\vec{S}$, incident upon a perfectly absorbing surface $P = \frac{S}{c}$ and if incident upon a perfectly reflecting surface $P = \frac{2S}{c}$.
- The electric and magnetic fields of a sinusoidal plane electromagnetic wave propagating in the positive x-direction can also be written as

  $E = E_m \sin(kx - \omega t)$ and

  $B = B_m \sin(kx - \omega t)$

  where ω is the angular frequency of the wave and k is wave number which are given by

  $\omega = 2\pi f$ and $k = \frac{2\pi}{\lambda}$
- The intensity of a sinusoidal plane electro-magnetic wave is defined as the average value of Poynting vector taken over one cycle.

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

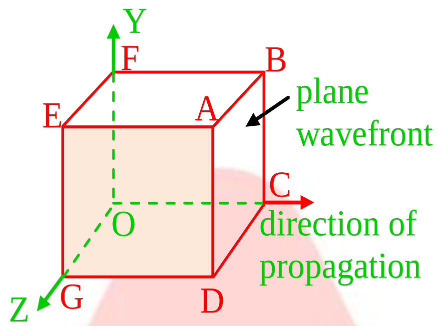
- The fundamental sources of electromagnetic waves are accelerating electric charges. For examples radio waves emitted by an antenna arise from the continuous oscillations (and hence acceleration) of charges within the antenna structure.
- Electromagnetic waves obey the principle of superposition.
- The electric vector of an electromagnetic field is responsible for all optical effects, for this reason electric vector is also called a light vector.

8 TRANSVERSE NATURE OF ELECTROMAGNETIC WAVES

Maxwell showed that a changing electric field produces a changing magnetic field and vice-versa. This alternate production of time 'varying electric and magnetic fields gives rise to the propagation of electromagnetic waves. The variation of electric field ($\vec{E}$) and magnetic field ($\vec{B}$) are mutually perpendicular to each other as well as the direction of the propagation of the wave i.e., the electromagnetic waves are transverse in nature.

Proof :

Consider a plane electromagnetic wave traveling along X-direction with its wave front in the Y-Z plane and ABCD is its portion at time t. The values of electric field and magnetic field to the left of ABCD will depend on x and t (and not on y and z as the wave under consideration is a plane wave propagating in x direction.



According to Gauss' law, the total electric flux across the parallelopiped' ABCDOEFG is zero because it does not enclose any charge,

i.e. $\oint \vec{E}.\vec{dS} = 0$

or $\oint_{ABCD} \vec{E}.\vec{dS} + \oint_{EFOG} \vec{E}.\vec{dS} + \oint_{ADGE} \vec{E}.\vec{dS} + \oint_{BCOF} \vec{E}.\vec{dS}$

$+ \oint_{OCDG} \vec{E}.\vec{dS} + \oint_{FBAE} \vec{E}.\vec{dS} = 0$ ....(i)

since electric field $\vec{E}$ does not depend on y and z, so the contribution to the electric flux coming from the faces normal to y and z axes cancel out in pairs.

i.e., $\oint_{OCDG} \vec{E}.\vec{dS} + \oint_{FBAE} \vec{E}.\vec{dS} = 0$ ....(ii)

and $\oint_{ADGE} \vec{E}.\vec{dS} + \oint_{BCOF} \vec{E}.\vec{dS} = 0$ ...(iii)

Using equation (ii) and (iii) in equation (i), we get

$\oint_{ABCD} \vec{E}.\vec{dS} + \oint_{EFOG} \vec{E}.\vec{dS} = 0$ ...(iv)

Now

$\oint_{ABCD} \vec{E}.\vec{dS} = \oint_{ABCD} E_x .dS\cos 0 = \oint_{ABCD} E_x \; dS = E_x \oint_{ABCD} dS$

($\because$ $\vec{E}_x$ is parallel to $\vec{dS}$)

$= E_x \times$ area of face ABCD $= E_xS$ ...(v)

and $\oint_{EFOG} \vec{E'}.\vec{dS} = \oint_{EFOG} E'_x dS\cos 180^\circ = E'_x \oint_{EFOG} dS$

($\because$ $\vec{E'}_x$ is antiparallel to $\vec{dS}$)

$= E'_x \times$ area of face EFOG $= E'_xS$ ....(vi)

where, E_x and E'_x are the x-components of electric field on the faces ABCD and EFOG respectively.

Substituting the values of equations (v) and (vi) in equation (iv), we get

$E_xS - E'_xS = 0$ or $S(E_x - E'_x) = 0$

$\because S \neq 0$

$\therefore E_x - E'_x = 0$ or $\boxed{E'_x = E_x}$

This equation shows that the value of the x-component of electric field does not change with time. In other words, electric field along x-axis is static.

Since the static electric field cannot propagate the wave, hence the electric field parallel to the direction of the propagation of the wave is zero.

i.e. $E'_x = E_x = 0$

It means, electric field is perpendicular to the direction of propagation of the wave.

similarly, it can be proved that the magnetic field is perpendicular to the direction of the propagation of the wave.

Since both electric and magnetic fields are perpendicular to the direction of the propagation of the wave, so electromagnetic wave is transverse in nature.

9 IMPORTANT POINTS TO REMEMBER

- *When a capacitor is connected across the battery through the connecting wires there is flow of conduction current, while through the gap between the plates of capacitor, there is flow of displacement current.*
- *Maxwell's equation are mathematical formulation of Gauss's law in electrostatics (I) Gauss's law in electromagnetism(II) faradays law of electromagnetic induction (III) and Ampere's circuital law (IV)*
- *Frequency of electromagnetic waves is its inherent characterstic when an electromagnetic wave travels from one medium to another, its wavelength changes but frequency remains unchanged.*
- *Ozone layer absorbs the ultra-violet rays from the sun and these prevents them from producing harmful effect on living organisms on the earth. Further it traps the infra-red rays and prevents them from escaping the surface of earth. It helps to keeps the earth's at atmosphere warm.*

10 VARIOUS PARTS OF ELECTROMAGNETIC SPECTRUM

S. No.	Radiation	Discover	How produced	Wavelength range	Frequency range	Energy range	Properties	Application
1.	γ-Rays	Henry Becquerel and Madam Cuire	Due to decay of radioactive nuclei.	10^{-14} m to 10^{-10} m	3×10^{-22} Hz to 3×10^{18} Hz	10^7eV-10^4eV	(a) High penetrating power (b) Uncharged (c) Low ionizing power	(a) Gives information on nuclear structure (b) Medical treatment etc
2.	X-Rays	Roentgen	Due to collisions of high energy electrons with	6×10^{-12} m to 10^{-9} m	5×10^{19} Hz to 3×10^{17} Hz	2.4×10^5 eV to 1.2×10^3eV	(a)Low penetrating power (b) other properties similar to γ-rays	(a) Medical diagnosis and treatment (b) Study of crystal structure

			heavy targets				except wavelength	(c) Industrial radiography
3.	Ultraviolet Rays	Ritter	By ionized gases, sun lamp spark etc.	6×10^{-10} m to 3.8×10^{-7} m	3×10^{17} Hz to 5×10^{19} Hz	2×10^{3}eV to 3eV	(a) All properties of light (b) Photoelectric effect	(a) To detect adulteration, writing and signature (b) Sterlization of water due to its destructive action on bacteria
4.	Visible light Subparts of visible spectrum (a) Violet (b) Blue (c) Green (d) Yellow (e) Orange (f) Red	Newton	Outer orbit electron transitions in atoms, gas discharge tube, incandescent solids and liquids	3.8×10^{-7} m to 7.8×10^{-7} m 3.9×10^{-7} m to 4.55×10^{-7} m 4.55×10^{-7} m to 4.92×10^{-7} m 4.92×10^{-7} m to 5.77×10^{-7} m 5.77×10^{-7} m to 5.97×10^{-7} m 5.97×10^{-7} m to 6.22×10^{-7} m 6.22×10^{-7} m to 7.80×10^{-7} m	8×10^{14} Hz to 4×10^{14} Hz 7.69×10^{14}Hz to 6.59×10^{14}Hz 6.59×10^{14}Hz to 6.10×10^{14}Hz 6.10×10^{14}Hz to 5.20×10^{14}Hz 5.20×10^{14}Hz to 5.03×10^{14}Hz 5.03×10^{14}Hz to 4.82×10^{14}Hz 4.82×10^{14}Hz to 3.84×10^{14}Hz	3.2eV to 1.6eV	(a) Sensitive to human eye	(a)To see objects (b) To study molecular structure

S. No.	Radiation	Discover	How produced	Wavelength range	Frequency range	Energy range	Properties	Application
5.	Infra-Red waves	William Herschell	(a) Rearrangement of outer orbital electrons in atoms and molecules. (b) Change of molecular vibrational and rotational energies (c) By bodies at high temperature	7.8×10^{-7} m to 10^{-3} m	4×10^{14}Hz to 3×10^{11}Hz	1.6eV to 10^{-3}eV	(a) Thermal effect (b) All properties similar to those of light except λ	(a) Used in industry, medicine and astronomy (b) Used for fog or haze photography (c) Elucidating molecular structure

6.	Microwaves	Hertz	Special electronic devices such as klystron tube	10^{-3} to 0.3 m	3×10^{11}Hz to 10^{9}Hz	10^{-3} eV to 10^{-5} eV	(a) Phenomena of reflection, refraction and diffraction	(a) Radar and teleco -mmunication. (b)Analysis of fine details of molecular structure
7.	Radio waves Subparts of Radio-spectrum	Marconi	Oscillating circuits	0.3 to few kms	10^{9}Hz to few Hz	10^{-3} eV to ≈ 0	(a) Exhibit waves like properties more than particle like properties	(a) Radio communication
(A) (B)	Super High Frequency (a) SHF Ultra High Frequency (b) UHF Very High Frequency (c) VHF			0.01 m to 0.1 m 0.1 m to 1 m 1 m to 10 m	3×10^{10}Hz to 3×10^{9}Hz 3×10^{9}Hz to 3×10^{8}Hz 3×10^{8}Hz to 3×10^{7}Hz		Radar, Radio and satellite communication (Microwaves), Radar and Television broadcast short distance communication, Television communication.	
	High Frequency (HF) Medium Frequency (MF) Low Frequency (LF) Very Low Frequency (VLF)			10m to 100m 100m to 1000 m 1000 m to 10000 m 10000 m to 30000 m	3×10^{7}Hz to 3×10^{6}Hz 3×10^{6}Hz to 3×10^{5}Hz 3×10^{5}Hz to 3×10^{4}Hz 3×10^{4}Hz to 10^{4}Hz		Medium distance communication Telephone communication, Marine and navigation use, long range communication. Long distance communication	

11 EARTH'S ATMOSPHERE AND ELECTROMAGNETIC WAVES

(i) The gaseous envelop surrounding the earth is called earth's atmosphere.

(ii) It mainly consists of nitrogen 78% and oxygen 21% alongwith a little portion of argon, carbon-di-oxide, water vapour, hydrocarbons, sulphur compounds and dust particles.

(iii) The density of atmospheric air goes on decreasing gradually as we go up.

(iv) The earth's atmosphere has no sharp boundary. However, it has been divided into various regions as given below:

(a) **Troposphere%** It extends upto a height of 12 km from earths surface. The temperature in this region decreases from 298K to 220K and conductivity increases. All climatic changes occur in this region.

(b) **Stratosphre%** It extends from 12 km to 50 km after troposhpere. At the upper part of this region, approximately 20km thick, most of ozone of atmosphere is concentrated. This layer is called as ozone layer. This layer absorbs very large portion of ultraviolet radiations coming from sun, therefore its temperature increases from 220K to 280K.

(c) **Mesosphere%** It extends from 50km to 80 km after stratosphere. In this region the temperature decreases from 280K to 180K

(d) **Ionosphere%** It extends from 80 km to 400 km after mesosphere. The temperature of this region rises from 180K to 700K. In this region ultraviolet radiation coming from sun cause ionisation, therefore this part mostly consists of free electrons and positive ions. The concentration of free electrons is found to be very large in a region beyond 110 km from earth's surface which extends vertically for a few kilometers and is called Kennelly Heaviside layer. Beyond this layer the concentration of free electrons decreases considerably until a height of about 250 km. Beyond it there is another layer of electrons, called Appleton layer.

(v) Greenhouse effect% The atmosphere is transparent to visible radiations, but most ifrared (heat) radiations are not allowed to pass through. The energy from the sun heats the earth which then starts emitting radiations like any other hot body. However, since the earth is much colder than sun, its radiations are mainly in the infra red region. These radiations are unable to cross the lower atmosphere and are reflected back. Low lying clouds also reflect back the infra red radiations. As such, the earth's surface warm at night. This phenomenon is called the Green house effect.

(vi) Propagation of Radio waves%

(a) Low frequency waves-the AM band% Radiowaves having wavelengths of 10m or more (frequency less than 30 Mhz) are said to constitute the AM band. The lower atmosphere is transparent to these waves, but the ionosphere reflects them back. A signal transmitted from a certain point can be received at another point in two possible ways-directly along the surface of the earth (called sky wave) and after reflection from ionosphere (called sky wave). Waves having frequencies upto about 1500kHz (Wavelength above 200m) are mainly transmitted through ground because low frequency sky waves lose their energy very quickly than the sky waves. Therefore, higher frequencies are mainly transmitted through sky. These two regions of the AM band are called medium wave and short wave bands respectively.

(b) High frequency waves-Television transmission% Above a frequency of about 40MHz the ionosphere does not reflect the wave toward the earth. The television signals have frequencies in the range 100-200 MHz. Therefore TV transmission via the sky is not possible-only direct reception via the ground is possible. Therefore, in order to have larger coverage, the transmission has to be done through very tall antennas. The height of transmitting antenna for TV telecast is given by h =

$$\frac{d^2}{2R_e}$$

where d is the radius of the area to be covered for TV telecast and Re is the radius of earth.