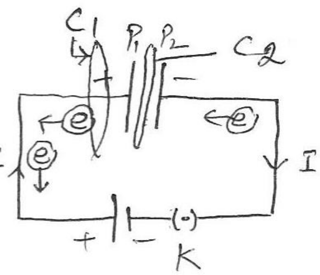
ELECTROMAGNETIC WAVES

Electromagnetic Waves

Inconsistency in Ampere's Circuital Law :- Consider the circuit with a capacitor connected to a cell through a key K. When the key is pressed; the electrons from P_1 are attracted towards the positive terminal of the battery. So plate P_1 acquires positive charge which increases with time. Similarly the negative terminal of the battery feeds electrons to P_2 which becomes negatively charged. As the charges grow; the potential difference between P_1 and P_2 increases till it becomes equal to that across the terminals of the cell. The capacitor is said to be fully charged. The current flows in the opposite direction as shown i.e. from P_2 to negative and from +ve to P_1. No current flows between the plates of the capacitor.



The circuit apparently shows the following two inconsistancies

(i) Discontinuity in Current :- A current 'I' flows into P_1 but no current flows out of it thus violating the criteria of continuity of current.

(ii) Ampere's law :- Considering loops C_1 and C_2 to the left and right of P_1 and applying the law; we get

$$\oint_{C_1} \vec{B} \cdot \vec{dl} = \mu_0 I \quad \text{—— (1)}$$

and

$$\oint_{C_2} \vec{B} \cdot \vec{dl} = \mu_0 (0) = 0 \quad \text{—— (2)}.$$

Move C_1 towards right and C_2 towards left to be infinitesimally close to the plate P_1.

We get $\oint_{C_1} \vec{B}\cdot\vec{dl} = \oint_{C_2} \vec{B}\cdot\vec{dl}$ — (3) [As the loops almost coincide].

The three equations cannot be simultaneously satisfied. Hence Maxwell suggested that Ampere's law in its present form is inconsistent.

<u>Displacement Current</u> :- Maxwell solved the anamoly by introducing the concept of displacement current. He suggested that; a current called displacement current flows between the plates of the capacitor. This current is given by $I_d = \epsilon_0 \frac{d\phi_E}{dt}$ and is caused by changing electric flux due to increasing electric field between the plates. causing ~~a change in~~ So Maxwell modified Ampere's law as

$$\oint_C \vec{B}\cdot\vec{dl} = \mu_0 (I + I_d) = \mu_0 \left[I + \epsilon_0 \frac{d\phi_E}{dt} \right] \quad (4)$$

1) <u>Equality of I and I_d</u> :-

We have $I_d = \epsilon_0 \frac{d\phi_E}{dt} = \epsilon_0 \frac{d}{dt}\int \vec{E}\cdot\vec{dS}$

$$= \epsilon_0 \frac{d}{dt}\int \left(\frac{\sigma}{\epsilon_0}\right) dS \quad \left[\because E = \frac{\sigma}{\epsilon_0} \text{ between plates of capacitor}\right]$$

$$= \frac{d}{dt}\int \sigma\, dS = \frac{d}{dt} q = I.$$

Hence the problem of apparent violation of discontinuity of current is solved.

(2) Consistancy of Ampere's Law

We have $\oint_{C_1} \vec{B}.\vec{dl} = \mu_0 [I + I_d] = \mu_0 I$ —(a) [No displacement current in C_1]

and $\oint_{C_2} \vec{B}.\vec{dl} = \mu_0 I_d = \mu_0 I$ —(b) [$I = 0$ thro' C_2 and $I_d = I$].

Hence equations (1) and (2) become consistent with Maxwell's modified form of the law.

Maxwell's equations :→ The following four equations are known as Maxwell's equations

$$\oint_S \vec{E}.\vec{dS} = \frac{\Sigma q}{\epsilon_0} \quad \text{(Gauss th. in electrostatics)} \quad —(1)$$

$$\oint_S \vec{B}.\vec{dS} = 0 \quad \text{[Gauss th in magnetism]} \quad —(2)$$

$$\text{Induced EMF} = \oint \vec{E}.\vec{dl} = -\frac{d\phi_B}{dt} \quad \text{(Faraday's law)} \quad —(3)$$

and

$$\oint_C \vec{B}.\vec{dl} = \mu_0 \left[I + \epsilon_0 \frac{d\phi_E}{dt}\right] \quad \text{(Maxwell's modified (Ampere's) law)} \quad (4)$$

The above equations with Lorentz's force equation $\vec{F} = q[\vec{E} + (\vec{v} \times \vec{B})]$ —(5) completely explain the phenomenon of Electromagnetism.

Prediction of EM Waves :- Maxwell considered a region of space devoid of all free charges and currents. The equations in this case take the following form:-

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

$$\int \vec{E}.\vec{dl} = -\frac{d}{dt}\int \vec{B}.\vec{dS} \quad \text{—— (6)}$$

and $\int \vec{B}.\vec{dl} = \mu_0 I_d = \mu_0 \epsilon_0 \frac{d\phi_E}{dt}$ — (7).

According to equation (6); magnetic field changing with time produces electric field and by equation (7); electric field changing with time produces magnetic field. As the field can exist in space, Maxwell predicted that an e m wave can exist and propagate through free space. The wave should be associated with a time varying electric and a time varying magnetic field each sustaining the other.

Production of EM Waves :- Consider a charge at rest. It is associated with a static electric field but no magnetic field. Hence it cannot emit EM Wave.

If the charge moves with a uniform velocity, it results in a steady current. Hence it is associated with a steady magnetic field and again cannot produce EM Wave.

However an accelerated charge is always associated with both time varying electric as well as magnetic field. An accelerated charge can Therefore emit E M Wave.

The EM wave can also be produced when a fast moving electron is made to hit a high atomic number metal Target. (Method of producing X - Rays).

When an electron in an atom jumps from a higher energy level to a lower energy level; ~~X - Ray~~ EM waves are produced.

Transverse Nature of Waves ⇒ The EM waves are transverse in nature. In an e m wave; we have

$\vec{E} \perp \vec{B} \perp \vec{v}$ (the direction of propagation of the wave).

The electric field between the plates of the capacitor is perpendicular to the plates and is directed from positive to the negative plate.

The magnetic field caused by the displacement current is along the perimeter of a circle parallel to the capacitor plates. So $\vec{B} \perp \vec{E}$

For a wave propagating along Z-direction; $\vec{E}$ may be along X and $\vec{B}$ along Y-direction or vice versa.

The electric and the magnetic fields vary sinusoidally and are in same phase i.e. reach their peak values or zero values at the same time.

We may write $E_x = E_0 \sin(kz - \omega t)$ and $B_y = B_0 \sin(kz - \omega t)$

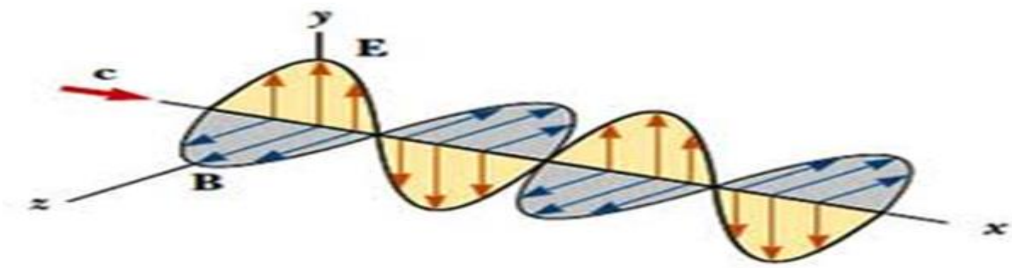
See diagram of EM Wave.

Useful Relations $k = \frac{2\pi}{\lambda}$ (Propagation vector). speed $= c = \frac{\omega}{k}$.

$c = \frac{1}{\sqrt{\mu_0 \epsilon_0}}$ (for vaccum).; $E_0/B_0 = c$; $v = \frac{1}{\sqrt{\mu \epsilon}}$ for a medium

Properties:

1. Variations in both electric and magnetic fields are in same phase. Hence both attain their maxima and minima simultaneously and at same position as shown below..



2. The directions of electric and magnetic fields are mutually perpendicular to each other and also to the direction of propagation of the wave.

3.The electric field intensity E and magnetic field intensity B are related as $c = \frac{E_0}{B_0}$ where E_0 and B_0 are the amplitudes of the respective fields and c is speed of light.

4. The velocity of electromagnetic waves in free space,
$c = 1 / \sqrt{\mu_0 \varepsilon_0}$

5. The velocity of electromagnetic waves in a material medium Is given by **$v = 1 / \sqrt{\mu\varepsilon}$** where μ and ε are absolute permeability and absolute permittivity of the material medium.

6. Electromagnetic waves obey the principle of superposition.

7. Electromagnetic waves carry energy as they propagate through space. This energy is divided equally between electric and magnetic fields.

8. Electromagnetic waves can transfer energy as well as momentum to objects placed in their paths.

9.For discussion of optical effects of em wave, more significance is given to electric field, E due to fact that electric force is much stronger than the magnetic field force. Therefore, electric field is called 'light vector'.

Different Parts of E M Spectrum

1. GAMMA-RAYS

WAVELENGTH RANGE: They overlap the upper limit wavelength of the x-ray. Their wavelength range is 10^{-14} m to 10^{-10} m.

FREQUENCY RANGE: The gamma rays have a frequency range of 3 X 10^{18} Hz TO 3 X 10^{22} Hz.

SOURCE: They are emitted by RADIOACTIVE SUBSTANCES

USES:

Provide INFORMATION ABOUT STRUCTURE OF NUCLEI,

Used in treatment of cancer

Sterilization of medical equipment after packing

Production of better verities of crops

ASTRONOMICAL RESEARCH, ETC.

2. X-RAYS

WAVELENGTH RANGE

THEIR WAVELENGTH RANGE IS 6 x 10^{-12} m TO 10^{-9} m.

frequency Range

The gamma rays have a frequency range of

3 X 1017 Hz TO 3 X 1019 Hz.

Source

They are emitted by bombaRDIng metal having large atomic number with fast moving electrons.

Uses

X-ray photography

Medical diagonostics

Used in treatment of cancer

Treatment of skin disease & tumors

Locating cracks and flaws in finished metal objects

Search of objectionable goods in luggage of travelers

Study of crystal structure

3.Ultra violet rays

Wavelength range

They overlap the upper limit wavelength of the x-ray. Their wavelength range is 6×10^{-10} m to 3.8×10^{-7} m.

Frequency range

The gamma rays have a frequency range of 8×10^{14} hz to 3×10^{17} hz.

Source

They are emitted in electric discharge through gaseous atoms and molecules are present in solar radiations.

Uses

Medical applications
Sterilization
Killing bacteria and germs in food stuff
Detection of invisible writing
Detection of forged documents
Study of finger prints

4. LIGHT WAVES OR VISIBLE SPECTRUM
WAVELENGTH RANGE
THEY occupy a band between infrared and uv waves.
THEIR WAVELENGTH RANGE IS 7.8 x 10-7 m to 3.8 x 10-7 m
frequency Range
The light waves have a frequency range of 4 x 1014 Hz to 8 x 1014 Hz.
Source
They are produced by excited Atoms and molecules & Black bodies.
Uses: Optics and Optical Instruments
Vision and photography
Decorative lighting

5. Infra red Rays

WAVELENGTH RANGE

THEY occupy a band between visible light and microwaves. THEIR WAVELENGTH RANGE IS 7.8×10^{-7} m TO 10^{-3} m.

Frequency Range

The Infra red rays have a frequency range of

$3 \text{ X } 10^{11}$ Hz TO $4 \text{ X } 10^{14}$ Hz.

Source

They are emitted by Molecules

Hot bodies

Are present in solar radiations.

Uses

In Industry

Medicine

Astronomy

Night vision devices Green house Revealing secret writings on ancient walls**.**

6. Micro waves

Wavelength range

THEY occupy a band between infrared and radiowaves.

Their wavelength range is 7.8×10^{-7} m TO 10^{-3} m.

Frequency range

The microwaves have a frequency range of

$3 \text{ X } 10^{11}$ hz TO $4 \text{ X } 10^{14}$ hz.

Source

They are emitted molecules

Hot bodies

Are present in solar radiations.

Uses

In industry

Medicine

Astronomy

Night vision devices

Green house

Revealing secret writings on ancient walls.

7. Radio Wave
WAVELENGTH RANGE
THEIR WAVELENGTH RANGE IS 0.3 m to A few km.
THEY occupy a band between microwaves and power frequencies.
frequency Range
The radio waves have a frequency range of 10^9 Hz to 3×10^{11} Hz .
Source
They are produced by Oscillating electronic circuits.
Uses
Radar
mobile telephony
analysis of atomic and molecular structure
Microwave ovens for cooking.

Sample Problems

Q1.In a plane *em* wave, the electric field oscillates sinusoidally at a frequency of 2.0×10^{10} Hz and amplitude of 48 Vm^{-1}.
(*a*) What is the wavelength of the wave?
(*b*) What is the amplitude of the oscillating magnetic field?
(*c*) Show that the average energy density of the electric field equals the average energy density of the magnetic field. [$c = 3 \times 10^8$ ms^{-1}]

Q2.What is the nature of waves used in photography during haze and fog? What is their wavelength range?
Ans. Infra red waves.
Wavelength range 7.5×10^{-7} m to 10^{-3} m

Q3.Find the wavelength of electromagnetic waves of frequency 4×10^9 Hz in free space. Give its two applications.

Ans. Given $\nu = 4 \times 10^9$ Hz

$$\therefore \quad \lambda = \frac{c}{\nu} = \frac{3 \times 10^8}{4 \times 10^9} \text{ m}$$

$$= \frac{30}{4} = \mathbf{7.5\ cm}$$

The waves are called microwaves.

Apllications of microwaves:
(*i*) Used in microwave ovens for cooking, baking, grilling.
(*ii*) Used in Radar and microwave communication links.
Q4.Name the electromagnetic radiations which are produced when high energy electrons are bombarded on a metal target.
Ans. *X*-rays.
Name the electromagnetic radiations having the wavelength range from 1 mm to 700 nm. Give its two important applications.
Ans. The radiations are called Infrared radiations.
Applications
(*i*) Used to relieve muscular pain in human body.
(*ii*) Used for cooking/remote control devices.