Electromagnetic waves

Displacement current: An electric current produces a magnetic field around it. Maxwell proposed that for logical consistency a changing electric field must also produce a magnetic field.

To demonstrate how a changing electric field gives rise to a magnetic field, the process of charging of a capacitor is considered.

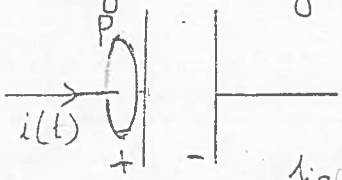


fig (i)

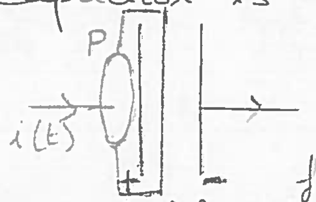


fig (ii)

To find the magnetic field at P a surface is chosen as indicated in fig (i) and applying Ampere's circuital law we have $B(2\pi r) = \mu_0 \, i(t)$.

Now considering a different surface as in fig (ii) that has the same boundary as in fig (i) but with the other end of the surface between the capacitor plates, the magnetic field is zero at P (according to Ampere's circuital law) since no current passes through the surface between the plates of a capacitor.

Therefore, Maxwell concluded that the inconsistency of Ampere's circuital law is due to the wrong assumption that in a circuit containing a capacitor no current flows between the plates of the capacitor. The conduction current flows from the plate A of the capacitor to the plate B through the wire. The electric field between the plates of the capacitor varies with time and produces a current equivalent to the conduction current called as the displacement current. Therefore, the modified Ampere's circuital law is

$$\oint \vec{B} \cdot \vec{dl} = \mu_0 [I_c + I_d]$$

$I_c \rightarrow$ conduction current $\quad I_d \rightarrow$ displacement current

Expression for displacement current

Using Gauss's law $\phi_E = EA$

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

As the charge q on the plates of the capacitor changes with time there is a current $i = dq/dt$.

$$\frac{d\phi_E}{dt} = \frac{1}{\epsilon_0}\frac{dq}{dt}.$$

$$\Rightarrow I_d = \epsilon_0 \frac{d\phi_E}{dt}.$$

Hence the Ampere - Maxwell law is written as

$$\oint \vec{B}\cdot\vec{dl} = \mu_0 I_c + \mu_0 \epsilon_0 \frac{d\phi_E}{dt} \quad \left[\because I_d = \epsilon_0 \frac{d\phi_E}{dt}\right]$$

If the above law is used to find the magnetic field at P the value is always non zero irrespective of the shape of the surface chosen.

Note: I_c and I_d are individually discontinuous but the two current together possess the property of continuity through any closed electrical circuit.

Consequences of displacement current

1. The laws of electricity and magnetism are more symmetrical. According to Faraday's law of induction there is an induced emf due to rate or change of magnetic flux or in other words a magnetic field changing with time gives rise to an electric field. Also, as a result of displacement current it can be stated that an electric field changing with time gives rise to a magnetic field.
2. This time dependent electric and magnetic fields give rise to each other and an important consequence of this symmetry is the existence of electromagnetic waves.

<u>Source of em waves</u>: An accelerated or oscillating electric charge radiates em waves.

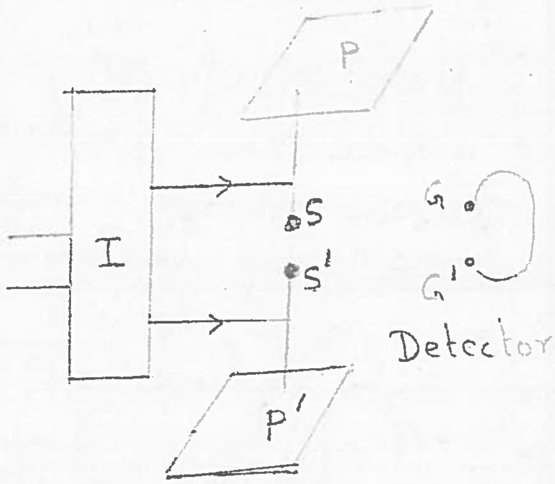
An oscillating electric charge produces an oscillating electric field in space which in turn produces an oscillating magnetic field. The oscillating magnetic field is then a source of an oscillating electric field and so on. The oscillating electric and magnetic fields thus regenerate each other as the wave propagates through space. The frequency of the em wave equals the frequency of oscillation of the charge.

<u>Hertz experiment</u>:

(1) Two large spheres S and S' are attached to two large metal plates P and P'.

2) The spheres are connected to the induction coil I.

(3) By means of the induction coil a sudden high voltage is applied across the gap. The voltage is high enough to ionise the air in the gap and a spark jumps the gap.



(4) Since the air is ionised, the spark gap consists of electrons and ions that oscillate back and forth.

(5) This process results in the production of em waves. The frequency of oscillation is determined by the inductance and capacitance of the coils or rods that form the gap.

$$\therefore \nu = \frac{1}{2\pi\sqrt{LC}}$$

<u>Detection</u>: The em waves reaching the gap of the

detector produces an electric field strong enough to establish a high potential difference between the gap GG' thus causing a spark. The spark across GG' establishes the detection of em waves.

When the gap in the detector is at right angles to the source gap the em waves are not detected. This demonstrates that em waves are transverse in nature.

<u>Note</u>: The Indian scientist, Jagdish Chander Bose, succeeded in producing and observing em waves of much shorter wavelength [25 mm to 5 mm]

Later Marconi, succeeded in transmitting em waves over distances ranging several kms. In fact his experiments marked the beginning of the field of communication using em waves

<u>Characteristics</u> <u>of</u> <u>em waves</u>

(1) EM waves are produced by accelerated or oscillating charge and these waves do not require any material medium for propagation.

(2) These waves travel in space with the speed of light where $\boxed{C = \frac{1}{\sqrt{\mu_0 \epsilon_0}}}$

(3) The variation of electric and magnetic field vectors are $\perp$ to each other and $\perp$ to the direction of propagation. Thus em waves are transverse in nature.

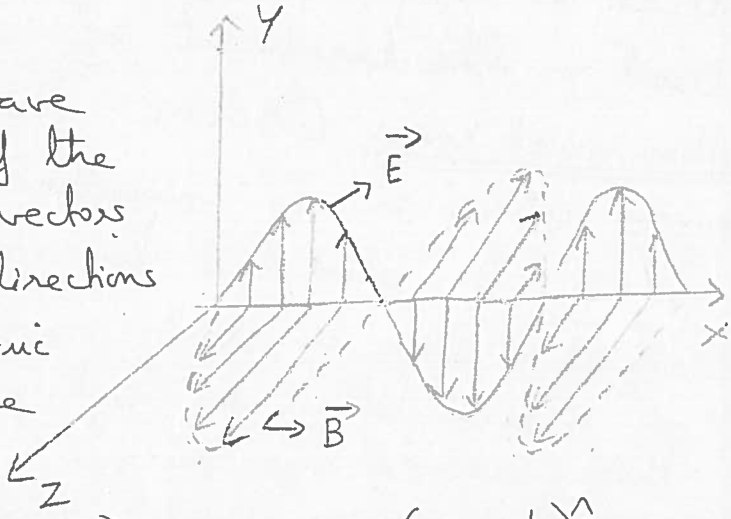
(4) The energy of em waves is divided equally between electric and magnetic field vectors.

(5) Sinusoidal variations occur simultaneously for electric and magnetic field vectors. ∴ Maxima and minima occur at the same place and at the same time. ∴ $\boxed{C = E_0/B_0}$

(6) The electric field vector is responsible for the optical effects of the em wave.

(7) These waves are not deflected by electric and magnetic fields.

(8) EM waves exert a force on the surface on which it is incident.



For propagation of EM wave along the +ve X direction if the electric and magnetic field vectors are along the Y and Z directions the expressions for the electric and magnetic field vectors are as follows

$$\vec{E_y} = E_0 \sin(kx - \omega t)\hat{j} \quad \text{or} \quad \vec{E_y} = E_0 \sin \frac{2\pi}{\lambda}(x - vt)\hat{j}$$

$$\vec{B_z} = B_0 \sin(kx - \omega t)\hat{k} \quad \vec{B_z} = B_0 \sin \frac{2\pi}{\lambda}(x - vt)\hat{k}$$

where $k = \frac{2\pi}{\lambda}$ and $\omega = 2\pi f$.

<u>Electromagnetic</u> <u>spectrum</u>. The classification of em waves according to frequency is the em spectrum. Since there is no sharp division between one kind of wave and the next, the classification is based on how the waves are produced.

Frequency : γ rays > X rays > uv > visible light > infrared > microwaves > radiowaves

(a) <u>Gamma rays</u> : [$<10^{-3}$ nm].

<u>Source</u> : Produced during nuclear reactions and also emitted by radio active nuclei

<u>Application</u> : (1) Used in medicine to destroy cancer cells.

(2) Provides information about atomic nuclei.

(b) X rays [1nm to 10^{-3} nm.]

Source: X rays are produced when a metal target is bombarded by high energy electrons.

Applications (1) For studying crystal structure.

(2) Used as diagnostic tool in medicine.

(3) Used in the treatment of certain forms of cancer.

(c) ultra violet rays [400nm to 1nm.]

Source: (i) Sun in an important source of uv radiations

(ii) It is also produced by special arc lamps.

Applications (i) Due to short wavelength it can be focussed into a narrow beam for high precision applications such as laser assisted eye surgery

(ii) to kill germs in water purifiers.

(iii) in burglar alarms.

(iv) for detection of forged documents.

uv radiations in large quantities has a harmful effect on humans. However most of it is absorbed in the ozone layer in the atmosphere at an altitude of 40-50 kms. The depletion of ozone layer caused by CFCs is therefore a matter of serious concern.

(d) Visible light [700nm to 400nm]

It is a part of the spectrum that can be detected by the human eye. It is produced by the excitation of valence electrons

(e) Infra red waves (1mm to 700nm)

Source: Hot bodies and molecules

Applications (i) Infra red lamps are used in physical therapy.

(ii) Infra red radiations play an important role in maintaining the average temperature of the earth because of the green house effect The incoming radiations from the sun that passes through the atmosphere is absorbed by the earth's surface and is reradiated as longer wavelength radiations. These radiations are absorbed by the green house gases such as carbondioxide and water vapour thus keeping the earth warm

(iii) Electronic devices such as LED's emit infrared radiations and are used in remote switches of electronic systems.

(f) Microwaves [0.1m to 1mm]

Source: Produced by special vacuum tubes called klystron and magnetron.

Applications (i) Due to its short wavelengths it is suitable for RADAR systems used in aircraft navigation. RADAR is also the basis for speed guns used to time fast balls, tennis serves and automobiles

(ii) In microwave ovens the frequency of the microwaves is selected to match the resonant frequency of water molecules (3 GHz) so that energy from the waves is transferred as kinetic energy of molecules. These molecules share the energy with neighbouring food molecules thus raising the temperature of any food containing water.

(iii) On account of smaller wavelength the microwaves can be transmitted as beam signals in a particular direction. Hence microwaves are better carriers of signals than radio waves

(g) <u>Radio</u> <u>waves</u> ($\lambda > 0.1m$)

<u>Source</u>: Produced by accelerated motion of charges

<u>Applications</u>: Used in radio and television communication systems

Amplitude modulated (AM) band	530 kHz – 1710 kHz
Short wave (SW) band	2 MHz – 54 MHz
Frequency modulated (FM)	88 MHz – 108 MHz
TV signals	54 MHz – 890 MHz
Cellular phones	UHF band.

<u>Note</u>: Radio signals in the short wave band are reflected by the ionosphere and therefore cover long distances.

TV signals cannot be propagated by ionospheric reflection because of its high frequencies due to which it penetrates the ionosphere

<u>Note</u> (i) Average energy density of the electric field is equal to the average energy density of the magnetic field.

Energy density of electric field $u_E = \frac{1}{2}\epsilon_0 E^2$

Using $E = cB$ and $c = \frac{1}{\sqrt{\mu_0 \epsilon_0}}$

$$u_E = \frac{1}{2}\frac{B^2}{\mu_0} = u_B .$$

(ii) An em wave carries energy and momentum. If the total energy transferred to a surface in time 't' is 'U' then the total momentum delivered is $p = U/c$

$$[\because U = mc^2 \Rightarrow p = U/c \,]$$

(iii) Intensity is the energy per unit area per unit time

$$I = \frac{U}{A \times t} = \frac{\text{Power}}{\text{Area}} .$$