Electromagnetic Waves

Displacement Current

- According to Ampere's circuital law, the line integral of the magnetic field $(\vec{B})$ around any closed path or circuit is equal to μ_0 times the total current

$$\therefore \oint \vec{B} \cdot \overrightarrow{dl} = \mu_0 I$$

- In the calculation of magnetic field, Ampere's circuital law brought in several contradictions. When a different surface was used to find the magnetic field, the result was different.

- It was concluded that a term was missing from the Ampere's circuital law—the electric field. This electric field passes the surfaces between the plates of the capacitor used.

- Each plate of a capacitor has an area *A*, and a total charge *Q*. Then, the magnitude of the electric field *E* is,

$$E = \frac{Q}{A \in_0}$$

- Using Gauss' law, the electric flux Φ_E through the surface is calculated as

$$\phi_E = EA = \frac{1}{\in_0}\frac{Q}{A} \times A$$
$$= \frac{Q}{\in_0}$$

- As the charge *Q* on the capacitor plates changes with time, there is a current,

  $i = dQ/dt$

$$\therefore \frac{d\phi_E}{dt} = \frac{d}{dt}\left(\frac{Q}{\in_0}\right) = \frac{1}{\in_0}\frac{dQ}{dt}$$
$$\Rightarrow \in_0 \frac{d\phi_E}{dt} = \frac{dQ}{dt} = i$$

  This is the missing term in Ampere's circuital law.

- The current carried by conductors due to the flow of charges is called conduction current, and the current (new term) due to the changing electric field is called displacement current or Maxwell's displacement current.

- Total current, i = Conduction current (i_c) + Displacement current (i_d)

$$\therefore i = i_c + i_d = i_c + \epsilon_0 \frac{d\phi_E}{dt}$$

- Outside the capacitor plate, $i = i_c$, and inside the capacitor plate, $i = i_d$
- Ampere–Maxwell law is given as

$$\oint B \cdot dl = \mu_0 i_c + \mu_0 \epsilon_0 \frac{d\phi_E}{dt}$$

The total current passing through any surface, of which the closed loop is the perimeter, is the sum of the conduction and displacement current.

Electromagnetic Waves

Sources of Electromagnetic Waves

- Accelerated charges radiate electromagnetic waves (Maxwell's theory).
- The frequency of an electromagnetic wave naturally equals the frequency of the oscillation of charge.

Nature of Electromagnetic Waves

- The electric and the magnetic field in an electromagnetic wave are perpendicular to each other and to the direction of propagation.
- Electric field E_x and magnetic field B_y are perpendicular to each other and to the direction (z) of propagation.

$\therefore E_x = E_0 \sin(kz - \omega t)$ ...(i)

and $B_y = B_0 \sin(kz - \omega t)$ ...(ii)

$$k = \frac{2\pi}{\lambda}$$

Here,
ω = angular frequency

k = wave/propagation vector

λ = wave length

t = time

- The speed of propagation of wave is ω/k. Using equations (i) and (ii) and Maxwell's equations, we obtain

$\omega = c\,k$, where $c = \frac{1}{\sqrt{\mu_0 \in_0}}$

- The magnitudes of the electric and the magnetic field in an electromagnetic wave are related as $B_0 = \frac{E_0}{c}$

- The velocity of light in material medium is given by $v = \frac{1}{\sqrt{\mu \in}}$

Here,
∈ = permittivity of the material medium

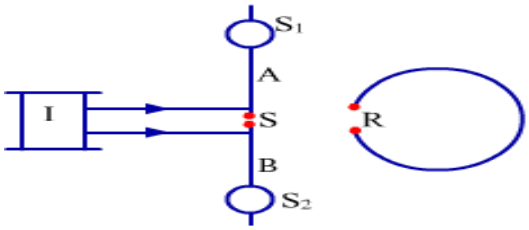
μ = permeability of the material medium

- Electromagnetic waves carry energy and momentum and they also exert pressure, called radiation pressure.

- When the total energy (U) is transferred to a surface in time t, the magnitude of the total momentum delivered to the surface is $p = \frac{U}{c}$, where c = speed of light

Production of Electromagnetic Waves: Hertz Experiment

The experiment was set up by Gustav Hertz in order to produce and detect electromagnetic waves. In the figure, S_1 and S_2 are two spheres situated near the ends of two straight rods A and B. The spheres are separated by a spark gap S. When the rods A and B are connected to the induction coil I, spark jumps across S and produces oscillating currents in A and B. Here, the two spheres act as plates of capacitors, while the rods A and B provide low inductance.



where I = Induction coil
A and B = straight rods
S = gap between A and B
R = gap between the loop of wire
S_1 and S_2 = spherical capacitors

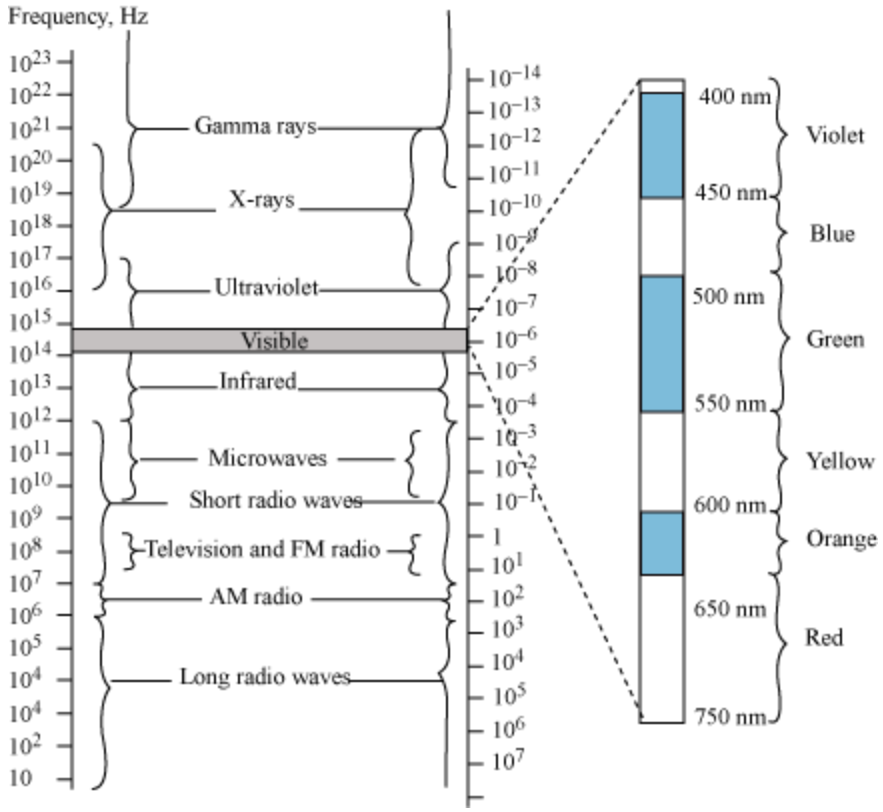
The receiver or detector is in the form of a metallic loop with gap R. This circuit is also an oscillating circuit in which the spark gap acts as a capacitor, while the loop provides the inductance. The tuning of the transmitter frequency of the receiver is made by sliding the spheres S_1 and S_2 along the rods A and B, respectively. When the two circuits are tuned, spark passes across R whenever spark passes across S.

Electromagnetic Spectrum

DIFFERENT TYPES OF ELECTROMAGNETIC WAVES			
Type	**Wavelength range**	**Production**	**Detection**
Radio	> 0.1 m	Rapid acceleration and decelerations of electrons in aerials	Receiver's aerials
Microwave	0.1 mm to 10 cm	Klystron valve or magnetron valve	Point contact diodes

Infra-red	0.4 mm to 750 nm	Vibration of atoms and molecules	Thermopiles, bolometer, infrared photographic film
Light	750 nm to 400 nm	Electrons in atoms emit light when they move from one energy level to a lower energy level.	The eye, photocells, photographic film
Ultraviolet	400 nm to 1 nm	Inner shell electrons in atoms moving from one energy level to a lower level	Photocells, photographic film
X-rays	10 nm to 10^{-2} nm	X-ray tubes or inner shell electrons	Photographic film, Geiger tubes, ionisation chamber
Gamma rays	$<10^{-2}$ nm	Radioactive decay of the nucleus	-do-

Different Types of Electromagnetic Waves



Uses of Electromagnetic radiations:

Light: It has very important role in our life. Human eye is sensitive to only this visible part of electromagnetic radiations. Anything which we able to see is because of the light.

(i) **Gamma rays:** These were first discovered radioactive emitted radiation. They are also present in cosmic radiations. Gamma rays have extensive applications,

* Most energetic electromagnetic radiations of wavelength less than 0.01 nm.

* These are used in the treatment of cancer.

* Used in γ-ray microscope.

* Acts as catalyst in the manufacturing of some chemicals.

* These are used to produce photoelectric effect.

* These rays are also used in radiography.

(ii) **X-rays:** William Rontgen was awarded Nobel prize in 1901 for his discovery of X-rays. X-rays are used in,

* Wavelength range between 0.01 nm to 10 nm.

* Fractured bones are located by the X-rays.

* X-rays are used in the treatment of cancer and skin diseases.

* These rays used to locate foreign bodies such as bullets, coins, pins etc in human body.

* X-rays are used in radiography.

* They are also used in the study of crystal structure.

(iii) **Ultraviolet radiations:** These rays were detected by J.W. Ritter in 1801. These are harmful to living tissues and are absorbed by the ozone layer present in our atmosphere. Its applications are,

* Wavelength range between 10 nm to 400 nm.

* UV rays are used as efficient sterilizers.

* UV rays are used to activate some chemical reactions.

* These are used in fluorescent lamps.

* UV rays used in identifying real gems and artificial gems.

* They are used in the treatment of skin diseases, diseases of the bone and rickets.

* They are used in synthesizing vitamin-D in our body.

* They are also used in the operation of photoelectric alarms.

(iv) **Visible light:** The electromagnetic radiations of wavelength from 400 nm to 800 nm are known as visible light. This part of the spectrum has been discovered by Newton by passing sunlight through a prism. Its applications are

* In photography

* In photosynthesis

* In enabling us to see objects around us

(v) **Infrared radiations:** It has heating effect which was first detected by W. Herschel in 1800. Its applications are,

* Wavelength range between 800 nm to 1 mm.

* Infrared spectrum is used to identify and determine molecular structure of a compound.

* Found suitable for long distance photography.

* Infrared photography is used to determine enemy movement during war, examine and detect forgery in old paintings

* These rays has a role in medical field, these are useful in the diagnosis of superficial tumours, dislocation of bones and in the treatment of sprains.

* It stimulates blood circulation.

* TV remote also uses infrared rays to control different settings.

* Infrared radiations from sun are used in the working of solar energy devices.

(vi) **Microwaves:** These are vastly used for experimental purposes. Also find applications in Radar, Satellite communication and microwave ovens.

* Wavelength range between 1 mm to 10 m.

* Found suitable for long distance photography.

* Infrared photography is used to determine enemy movement during war, examine and detect forgery in old paintings.

* These rays have role in medical field. These are useful in the diagnosis of superficial tumors, dislocation of bones and in the treatment of sprains.

* It stimulates blood circulation.

(vii) **Radio waves:** As there name suggest, these waves are used in radio and television.

* Wavelength range above 10 m.

* Short wavelength radio waves are used in communication systems including satellite systems, Radars and TV broadcasting.

* Longer wavelength radio waves are used in radio broadcasting.