9 - ELECTROMAGNETIC WAVES

9.1 Maxwell's Theory of Electromagnetic Waves

Maxwell presented in the form of differential equations,

(1) Gauss's law for electricity as $\oint E \cdot dS = \frac{q}{\epsilon_0}$

describing charge and the electric field,

(2) Gauss's law for magnetism as $\oint B \cdot dS = 0$

describing the magnetic field,

(3) Faraday's law of induction as $\oint E \cdot dS = - \frac{d\Phi_B}{dt}$

describing the electrical effect of a changing magnetic field and

(4) Ampere's law as extended by Maxwell, $\oint B \cdot dl = \mu_0 \left(\epsilon_0 \frac{d\Phi_E}{dt} + i \right)$

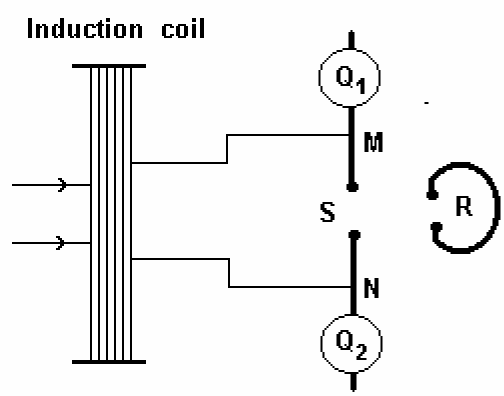
describing the magnetic effect of a changing electric field or of a current.

While correlating these equations, he postulated the existence of a missing term, 'i' in Ampere's law which he called the displacement current. Using these equations, he established his electromagnetic theory predicting the existence of electromagnetic radiation propagating in space in a wave form.

He also showed that the velocity of these waves is equal to the velocity of light in vacuum and deduced therefrom that light waves are electromagnetic waves.

9.2 Hertz's Experiment

The figure shows a simple experimental set-up of Hertz to produce electromagnetic waves in the laboratory.

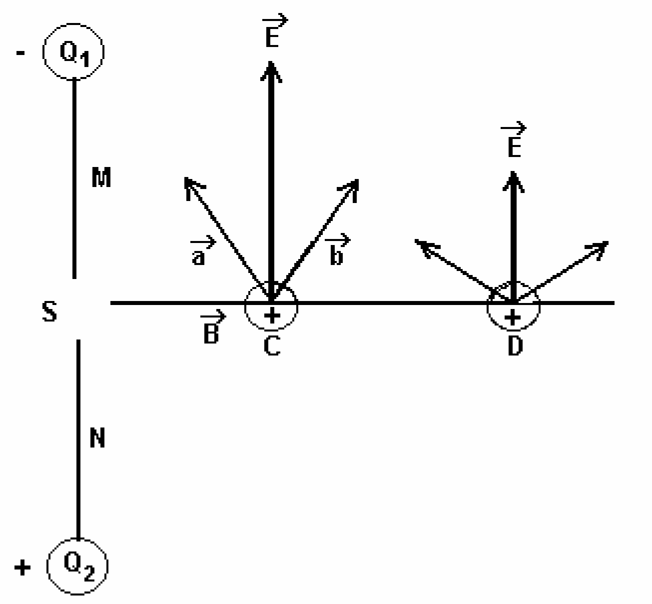


Two metallic spheres, Q_1 and Q_2, which constitute a capacitor are connected to metallic rods, M and N, which behave as an inductor with a spark gap S between them. A large potential difference is obtained with the help of induction coil to produce spark in the spark gap. Such an arrangement can be considered as an L-C oscillator circuit and is also known as a Hertzian dipole. At any instant when Q_1 has a positive charge, Q_2 has the same amount of negative charge. The polarity on the spheres Q_1 and Q_2 keep changing with a definite time period with charge passing through the spark gap.

A second spark gap, R, is arranged to detect the emission of the electromagnetic waves. Q_1 and Q_2 are arranged by sliding them on the rod to produce spark in spark gap R due to resonance.

Suppose the spheres are charged as shown in the figure (next page) at any instant of time.

The electric intensity at points C on the perpendicular bisector of Q_1Q_2 are shown by $\vec{a}$ and $\vec{b}$ due to the charged spheres Q_1 and Q_2 respectively, the resultant of which is $\vec{E}$ parallel to MN as shown in the figure. Similarly, the electric field intensity at D is also parallel to MN but is of the smaller magnitude. Thus there is a gradual decrease in the intensity of the electric field at a given instant as we move away from MN.

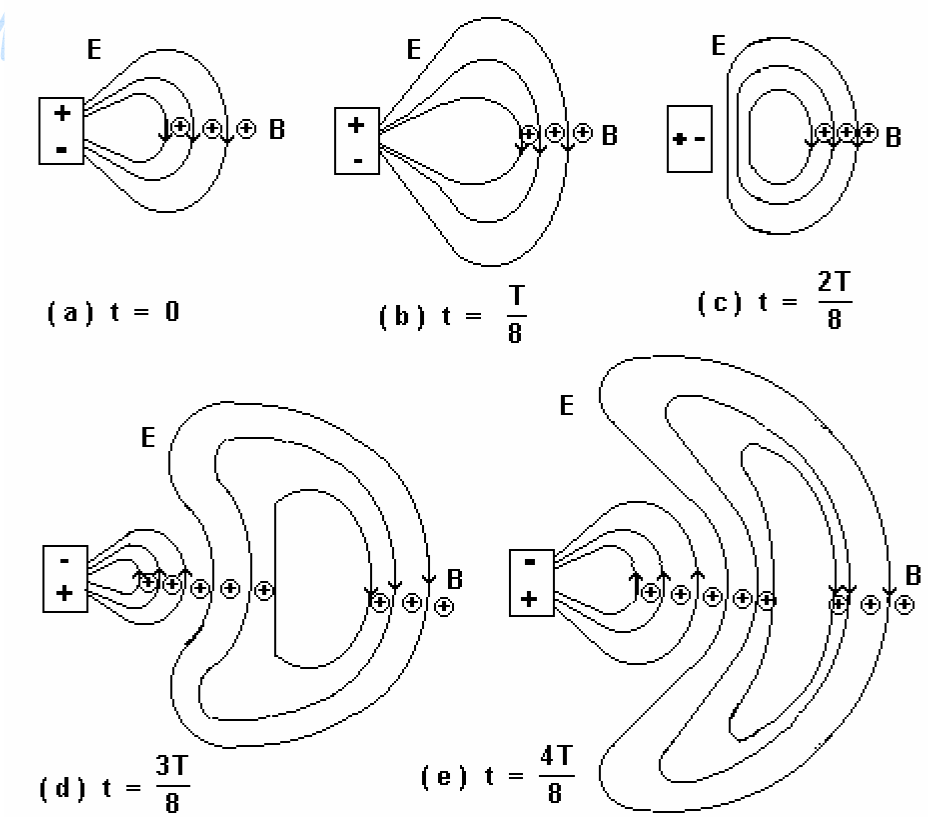


As the spark is produced in the spark gap, electrons flow from the sphere Q_1 to Q_2 reducing negative charge on Q_1 and positive charge on Q_2. With one half cycle of time elapsing, the charge on Q_1 becomes positive and that on Q_2 negative. Now the electric fields at C and D are in opposite directions.

Such periodic sparking results in vertical oscillations of electrons which in turn produces an oscillating electric field in space. Also the oscillations of the electrons give rise to a periodically changing electric current. This produces a periodically oscillating magnetic field at points such as C and D, the direction of which is perpendicular to that of the electric field as can be known using Ampere's right hand rule.

The Process of Emission of Electromagnetic Waves

The Hertzian dipole is shown in the figure.



Let the dipole moment, p, of this dipole at time, t, be given by

$$p = p_0 \cos \omega t.$$

The electric field lines in the plane of the paper and magnetic field lines perpendicular to the plane of the paper are shown in the figure.

Figures (a) and (b) show the state of the dipole and the corresponding electric and magnetic field lines at times t = 0 and t = T / 8 respectively.

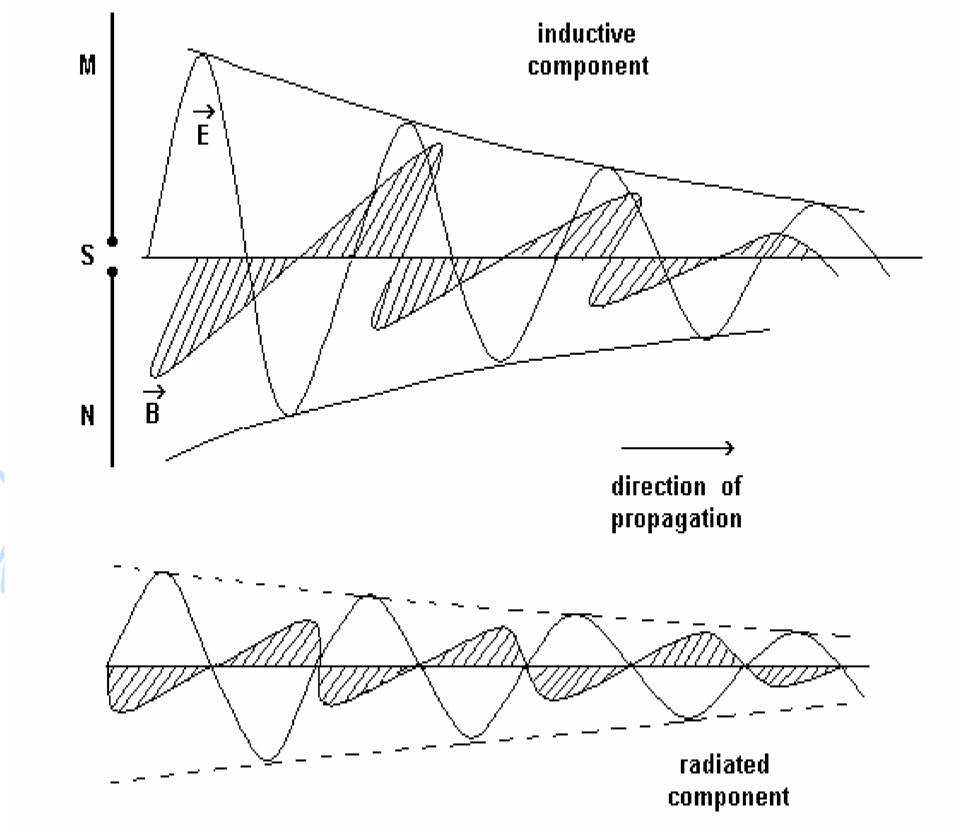
At time t = T / 4, the dipole moment becomes zero. In this case, the electric and the magnetic

field lines form closed loops and are de-linked from the dipole as shown in the figure (c).

At time t = 3T / 8, the electric charges on the dipole get reversed and the electric and magnetic field lines get again linked with the dipole. Meanwhile, the field lines which had formed closed loops move forward and travel some distance as shown in figure (d). At t = T / 2, the situation is as shown in figure (e).

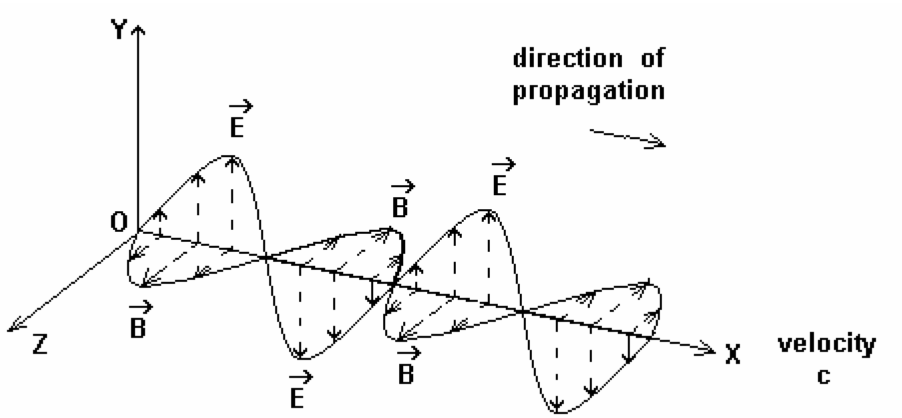
So, during every t = T / 2 time, due to the oscillations of the dipole, closed loops of the electric and magnetic fields are continuously formed and are transmitted in space after getting dissociated from the dipole.

According to Maxwell's theory, the electric and the magnetic fields at all points on the path of propagation of the electromagnetic wave do not come into existence instantaneously, but the effect travels in free space at the velocity of light. Hence the phase of the oscillations continuously decrease along the path of the wave. The position of the fields at any particular instant is shown in the figures.



In the region close to the oscillations of the charges, the phase difference between the $\vec{E}$ and $\vec{B}$ fields is equal to π / 2. Their magnitude quickly falls as per 1 / r^3 (where r is the distance from the source). These components of the transmitted waves are called the inductive components.

At large distance, the phase difference between $\vec{E}$ and $\vec{B}$ is zero. Their magnitudes fall as per 1 / r. These components of the fields are known as radiated components.



Thus, $\vec{E}$ and $\vec{B}$ fields oscillate in mutually perpendicular planes,

perpendicular to the direction of propagation of the wave. Both $\vec{E}$ and $\vec{B}$ values increase from zero to maximum with the passage of time and then start decreasing and become zero again. Then, the direction of the fields get reversed, become maximum in the reverse direction and increase to zero. Thus oscillations of the fields continue as the wave passes through any point.

The energy and frequency of the electromagnetic waves is respectively equal to the kinetic energy and frequency of oscillations of the charges oscillating between the two spheres.

For electromagnetic waves, c (velocity) = λ (wavelength) $\times$ f (frequency).

Seven years after Hertz's experiment, Acharya Jagdishchandra Bose generated electromagnetic waves of wavelength 5 to 25 mm. At the same time, Italian scientist, Marconi, successfully transmitted electromagnetic waves upto a distance of several miles.

9.3 Characteristics of Electromagnetic Waves

(i) Representation in the form of equations: With reference to the figure (previous page), the radiated components of electric and magnetic field of the electromagnetic wave can be represented by the equations,

$$\vec{E} = [E_0 \sin (\omega t - kx)] \hat{j} \quad \text{and} \quad \vec{B} = [B_0 \sin (\omega t - kx)] \hat{k}$$

(ii) $\vec{E}$ and $\vec{B}$ are related by the equation, $\frac{E}{B} = c$ (velocity of light)

(iii) Maxwell derived the equation for the velocity of electromagnetic wave in vacuum (free space) as

$c = \frac{1}{\sqrt{\mu_0 \varepsilon_0}}$, where, $\mu_0 = 4\pi \times 10^{-7}$ N A^{-2} is the permeability of free space and

$\varepsilon_0 = 8.85 \times 10^{-12}$ $C^2 N^{-1} m^{-2}$ is the permittivity of free space.

Using these values of μ_0 and ε_0, $c = 2.98 \times 10^8$ m s^{-1}.

This value of c is equal to the velocity of light in vacuum indicating that light is also a form of electromagnetic wave.

The velocity of the electromagnetic waves propagating in any medium is given as

$v = \frac{1}{\sqrt{\mu \varepsilon}}$, (μ = permeability of the medium and ε = permittivity of the medium)

Relative permeability, $\mu_r = \frac{\mu}{\mu_0}$ and relative permittivity, $\varepsilon_r = \frac{\varepsilon}{\varepsilon_0} = K$

where, K = dielectric constant of the medium.

$$\therefore \; v = \frac{1}{\sqrt{\mu_0 \mu_r \varepsilon_0 \varepsilon_r}} = \frac{1}{\sqrt{\mu_0 \varepsilon_0 \mu_r K}} = \frac{c}{\sqrt{\mu_r K}}$$

The refractive index of the medium, $n = \frac{c}{v} = \sqrt{\mu_r K} = \sqrt{\mu_r \varepsilon_r}$

(iv) Electromagnetic waves are transverse waves.

(v) Electromagnetic waves possess energy.

(vi) Electromagnetic waves exert pressure on a surface and impart linear momentum to it when they are incident on it.

If U is the energy of electromagnetic waves incident on a surface of unit area per second normal to it and is completely absorbed, then pressure exerted is given by $p = \frac{U}{c}$ which is also the momentum of electromagnetic radiation transferred to it.

(vii) Electromagnetic field prevails in the region where the electromagnetic waves propagate. The electromagnetic energy per unit volume in the region (energy density)

$$\rho = \rho_E + \rho_B = \frac{1}{2}\varepsilon_0 E^2 + \frac{B^2}{2\mu_0}$$

This formula is based on formulae for energy of capacitor and a solenoid where the fields are stationary. In electromagnetic waves, fields oscillate as per sine or cosine function. Hence replacing them by their rms values,

$$\rho = \frac{1}{2}\varepsilon_0 E_{rms}^2 + \frac{B_{rms}^2}{2\mu_0}$$

Putting $B_{rms} = \frac{E_{rms}}{c}$, $\frac{1}{\mu_0} = \varepsilon_0 c^2$,

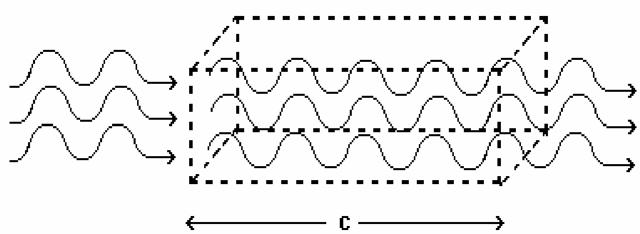
$$\rho = \frac{1}{2}\varepsilon_0 E_{rms}^2 + \frac{E^2_{rms}}{2c^2} \cdot \varepsilon_0 c^2 = \frac{1}{2}\varepsilon_0 E_{rms}^2 + \frac{1}{2}\varepsilon_0 E_{rms}^2$$

$$\therefore \quad \rho = \varepsilon_0 E_{rms}^2$$

(viii) "The intensity of radiation (I) is defined as the radiant energy passing through unit area normal to the direction of propagation in one second."

$$\therefore \quad I = \frac{\text{Energy / time}}{\text{Area}} = \frac{\text{Power}}{\text{Area}}$$

As shown in the figure, the radiant energy passing through unit area in one second is confined to a volume of length equal to c. If ρ is the energy density, then the energy in the above volume = $\rho \cdot c$.



$$\therefore \quad I = \rho \cdot c = \varepsilon_0 \, c E_{rms}^2$$

(ix) In the region far away from the source, electric and magnetic fields oscillate in phase and are called radiated components of electromagnetic radiation.

9.4 Electromagnetic Spectrum

The electromagnetic waves have wavelengths ranging from 10^{-15} m to 10^{8} m. Human eyes are sensitive to visible light having wavelengths ranging from 4000 A° to 8000 A°. The classification of electromagnetic waves is referred to as the electromagnetic spectrum. The electromagnetic waves in increasing order of wavelengths and decreasing frequencies are (i) γ-rays, (ii) X-rays, (iii) ultraviolet rays, (iv) visible light, (v) infrared rays, (vi) microwaves, (vii) short radio waves and (viii) long radio waves. γ-rays have wavelengths less than 1 A° whereas radio waves have wavelengths more than 1 m. There are no sharp boundaries dividing the various sections of the electromagnetic spectrum.

9.5 Electromagnetic radiation and Earth's atmosphere

Processes like reflection, refraction, polarization, dispersion and absorption take place when electromagnetic rays coming from the Sun pass through different media in Earth's atmosphere and reach the surface of the Earth. The Earth's atmosphere consists of Troposphere (upto about 15 km), Stratosphere (15 to 50 km), Mesosphere (50 to 80 km) and Thermosphere (80 to 110 km). The important points to be noted about the Earth's atmosphere are:

(1) The density of the atmosphere decreases as we go higher. There is no sharp boundary between the different layers.

(2) In the uppermost layer (i.e., ionosphere) there is a small amount of free electrons and positive ions.

(3) The layers other than the ionosphere are electrically neutral.

(4) Water molecules are present mostly in the lowermost layer (Troposphere).

(5) Ozone gas (O_3) is present at the height ranging between 30 to 50 km. The O_3 molecules are produced by dissociation of O_2 molecules.

(6) The Earth's atmosphere is bound to the Earth due to the gravitational field of the Earth.

Green house effect:

Of all the wavelengths of the electromagnetic waves, Earth's atmosphere is transparent to the visible light. The infrared radiations from the Sun are absorbed in the atmosphere. During the day time, the Earth's surface and various objects get heated and emit infrared radiations which are absorbed by molecules like CO_2, H_2O and re-emitted to the surface of the Earth. Thus heat energy is trapped in the lower atmosphere and its temperature is maintained. This is known as the Green house effect. Infrared rays are known as heat rays as they are responsible for producing warmth experienced during night. Some pollutants also contribute to the green house effect. In the absence of the green house effect, the average temperature of the lower atmosphere would have been much less. The harmful ultraviolet radiations and all wavelengths less than 3000 A° get absorbed in the Ozone layer which acts as a protective layer for us. Certain gases like Chloro-Fluoro Carbons (CFCs) used in refrigerator cause damage to the Ozone layer.

9.6 Electromagnetic waves and communication

Electromagnetic waves have revolutionized the field of communication. Waves of different frequencies interact differently with different media on earth and hence are used for different types of communications. They are broadly known as radio waves.