ELECTROMAGNETIC WAVES

Introduction

James Clerk Maxwell argued that if a changing magnetic field can produce an electric field, then a changing electric field must also produce a magnetic field.

Maxwell formulated a set of equations involving electric and magnetic fields, and their sources, the charge and current densities. These equations are known as Maxwell's equations. Together with the Lorentz force formula, they mathematically express all the basic laws of electromagnetism.

The most important prediction to emerge from Maxwell's equations is the existence of *electromagnetic waves, which are (coupled) time- varying electric and magnetic fields that propagate in space*. Hertz, in 1885, experimentally demonstrated the existence of electromagnetic waves. Its technological use by Marconi and others led in due course to the revolution in communication.

Displacement Current

As we know an electrical current produces a magnetic field around it. To see how a changing electric field gives rise to a magnetic field, let us consider the process of charging of a capacitor and apply Ampere's circuital law

$\oint \vec{B} \bullet d\vec{l} = \mu_0 I$ to find magnetic field at a point outside the capacitor. Maxwell found that Ampere's circuital law is inconsistent and requires modification. This led to the concept of ***displacement current***.

ie., The source of a magnetic field is not *just* the conduction electric current due to flowing charges, but also the time rate of change of electric field. More precisely, the total current i is the sum of the conduction current denoted by i_c, and the displacement current denoted by i_d (= $\varepsilon_0 (d\phi_E/dt)$).

So we have $i = i_c + i_d = i_c + e_0 (d\phi_E/dt)$)

This means that outside the capacitor plates, we have only conduction current $i_c = i$, and no displacement current, i.e., $i_d = 0$. On the other hand, inside the capacitor, there is no conduction current, i.e., $i_c = 0$, and there is only displacement current, so that $i_d = i$.

Maxwell's Equations

1. Gauss' law of electrostatics $\oint_S \vec{E} \bullet d\vec{S} = \frac{q}{\varepsilon_0}$

2.Gauss' law of magnetism $\int \vec{B} \bullet d\vec{S} = 0$

3. Faraday's law $\int \vec{E} \bullet d\vec{\ell} = -\frac{d\varphi_B}{dt}$

4.Ampere-Maxwell law $\int \vec{B} \bullet d\vec{\ell} = \mu_0 I_C + \mu_0 \varepsilon_0 \frac{d\varphi_E}{dt}$

Electromagnetic Waves

How are electromagnetic waves produced?

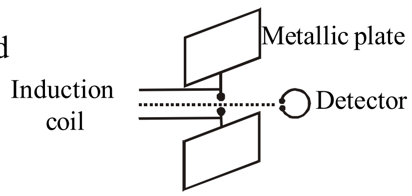
Stationary charges or charges in uniform motion (steady currents) cannot be sources of electromagnetic waves. The former produces only electrostatic fields, while the latter produces magnetic fields that, however, do not vary with time. It is an important result of Maxwell's theory that accelerated charges radiate electromagnetic waves. Consider a charge oscillating with some frequency. (An oscillating charge is an example of accelerating charge.) This produces an oscillating electric field in space, which produces an oscillating magnetic field, which in turn, is a source of oscillating electric field, and so on. The oscillating electric and magnetic fields thus regenerate each other, as the wave propagates through the space. The frequency of the electromagnetic wave naturally equals the frequency of oscillation of the charge. The energy associated with the propagating wave comes at the expense of the energy of the source – the accelerated charge.

The experimental demonstration of electromagnetic wave had to come in the low frequency region (the radio wave region), as in the Hertz's experiment (1887). Hertz's successful experimental test of Maxwell's theory created a sensation and sparked off other important works in this field. Two important achievements in this connection deserve mention. Seven years after Hertz, Jagdish Chandra Bose, working at Calcutta succeeded in producing and observing electromagnetic waves of much shorter wavelength (5 mm to25 mm).

Hert'z experiment

Construction

This experiment consists of two large metallic plates, which is connected to brass spheres. These two spheres are separated by a small distance. An induction coil is connected to this spheres. A closed ring is used to detect the electromagnetic waves.



Working

The metal plates are charged to a high voltage by an induction coil. When the voltage is high, the plates are discharged. Thus electromagnetic waves are produced.

The circuit is equivalent to an L-C circuit, the coil provides inductance and metal plates provide capacitance.

$$f = \frac{1}{2\pi\sqrt{LC}}$$

This electromagnetic wave induces an electric field in the ring and spark is produced. By this experiment the electromagnetic waves of wavelength 5m could be produced)

(for Hertz's experiment palets used should be large and induction coil capable of prodicing 1000V)

In the same year, Guglielmo Marconi in Italy followed Hertz's work and succeeded in transmitting electromagnetic waves over distances of many kilometres. Marconi's experiment marks the beginning of the field of communication using electromagnetic waves.

Characteristics of Electromagnetic waves

1.Electromagnetic waves propagate in the form of mutually perpendicular magnetic and electric fields. The direction of propagation of wave is perpendicular to both magnetic and electric field vector

2. Velocity of electromagnetic waves in free space is,

$$c = \frac{1}{\sqrt{\mu_o \varepsilon_o}}$$

The speed of electromagnetic wave in a material medium is given by

$$v = \frac{1}{\sqrt{\mu\varepsilon}} = \frac{c}{\sqrt{\mu_r \varepsilon_r}}$$

3.The ratio of magnitudes of electric and magnetic field vectors in free space is constant

i.e., $c = \frac{E}{B}$. E and B are in same phase.

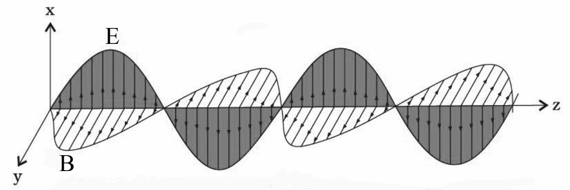
4. No medium is required for propagation, trasverse in nature

5. Electromagnetic waves show properties of reflection, refraction, interference, diffraction and polarisation.

6. Electromagnetic waves have capability to carry energy from one place to another.

Mathematical Expression

Consider a plane electromagnetic wave travelling along the Z direction. The electric and magnetic fields are perpendicular to the direction of wave motion (X and Y direction).



A linearly polarised electromagnetic wave, propagating in the *z*-direction with the oscillating electric field **E** along the *x*-direction and the oscillating magnetic field **B** along the *y*-direction.

The electric field vector along the Y direction.

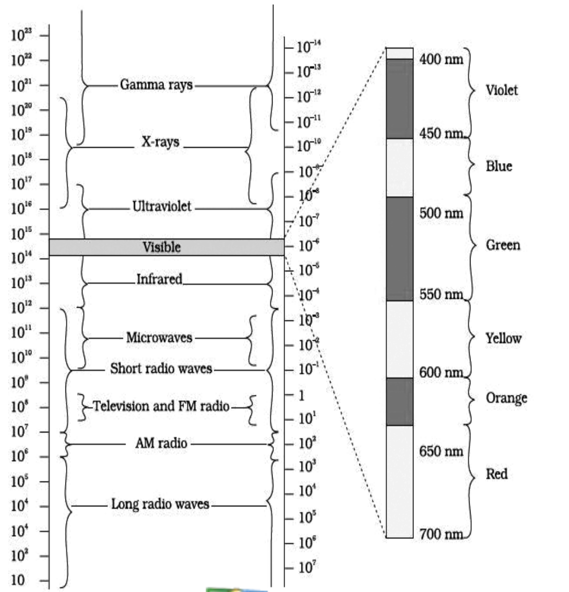
$E_X = E_0 \sin (kz-\omega t)$

And $B_Y = B_0 \sin (kz-\omega t)$

where E_0 is the amplitude of electric field vector, B_0 is the amplitude of magnetic field vector, ω is the angular frequency and k is related to the wave length λ of the wave, $k=2\pi/\lambda$

Electromagnetic Spectrum

Newton obtained the spectrum of sunlight and observed that all colours from red to violet continuously in the sun's spectrum. Maxwell predicted the existence of electromagnetic waves, the only familiar electromagnetic waves were the visible light waves. The existence of ultraviolet and infrared waves was barely established. We now know that, electromagnetic waves include visible light waves, X-rays, gamma rays, radio waves, microwaves, ultraviolet and infrared waves. The classification of em waves according to frequency is the electromagnetic spectrum There is no sharp division between one kind of wave and the next. The classification is based roughly on how the waves are produced and/or detected.



a) Radio waves

Radio waves are produced by the accelerated motion of charges in conducting wires. They are used in radio and television communication systems. They are generally in the frequency range from 500 kHz to about 1000 MHz.

b) Microwaves

Microwaves (short-wavelength radio waves), with frequencies in the gigahertz (GHz) range, are produced by special vacuum tubes (called klystrons, magnetrons and Gunn diodes). Due to their short wavelengths, they are suitable for the radar systems used in aircraft navigation. . Microwave ovens are an interesting domestic application of these waves. (In such ovens, the frequency of the microwaves is selected to match the resonant frequency of water molecules so that energy from the waves is transferred efficiently to the kinetic energy of the molecules. This raises the temperature of any food containing water.)

c) Infrared waves

Infrared waves are produced by hot bodies and molecules. Infrared waves are sometimes referred to as heat waves. Infrared lamps are used in physical therapy. Infrared and are widely used in the remote switches of household electronic systems such as TV, video recorders etc. Infrared radiation also plays an important role in maintaining the earth's warmth or average temperature through the greenhouse effect.

d) Visible rays

It is the part of the spectrum that is detected by the human eye. It runs from about 4×10^{14} Hz to about 7×10^{14} Hz or a wavelength range of about 700 – 400 nm. Visible light emitted or reflected from objects around us provides us information about the world.

e) Ultraviolet rays (UV)

It covers wavelengths ranging from about 4×10^{-7}m to 6×10^{-10} m (0.6 nm to 400 nm)). UV radiation is produced by special lamps and very hot bodies. The sun is an important source of ultraviolet light. UV light in large quantities has harmful effects on humans. Exposure to UV radiation induces the production of more melanin, causing tanning of the skin. UV radiation is absorbed by ordinary glass. Hence, one cannot get tanned or sunburn through glass windows. Due to its shorter wavelengths, UV radiations can be focussed into very narrow beams for high precision applications such as eye surgery. UV lamps are used to kill germs in water purifiers.

f) X-rays

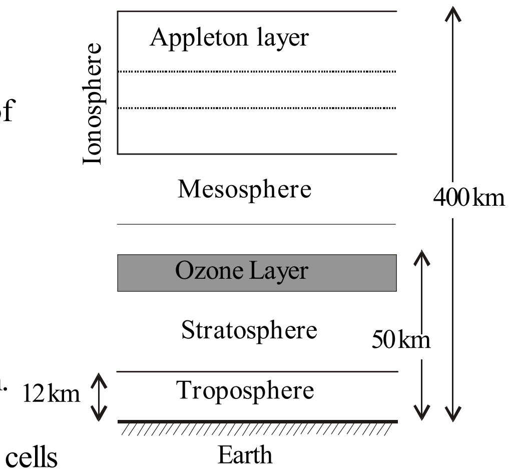
We are familiar with X-rays because of its medical applications. It covers wavelengths from about 10^{-8}m to 10^{-13}m (4nm-10 nm). One common way to generate X-rays is to bombard a metal target by high energy electrons. X-rays are used as a diagnostic tool in medicine and as a treatment for certain forms of cancer.

g) Gamma rays

They lie in the upper frequency range of the electromagnetic spectrum and have wavelengths of from about 10^{-10} m to less than 10^{-14}m. This high frequency radiation is produced in nuclear reactions and also emitted by radioactive nuclei. They are used in medicine to destroy cancer cells.

Earth's Atmosphere

The envelop of air surrounding the earth is called the earth's at mosphere. It mainly consists of oxygen and nitrogen along with small amount of argon, carbon dioxide, water vapour , hydrocarbons, sulphur compounds, dust particles etc. The density of earth's atmosphere goes on decreasing gradually as we go up. The earth's atmosphere has no sharp boundary; for convenience it has been devided into a number of layers.



1.Troposphere

It is the lowest layer .This layer extends up to a height of 12 Km from the earths surface. The temperature of this layer decreases with height (17^0 C to 53^0 C) .This layer is rich in water vapor.

2. Stratosphere

Stratosphere is extending between 12Km to 50Km above the earth.The upper region of stratosphere is called ozone layer (30 to 50Km) .Ozone is concentrated in this region.

Ozone Layer

The ultraviolet radiation from the sun is harmful to living cells and plants.Ozone layer absorbs these radiations and protects the plants and living organisms.

3. Mesosphere

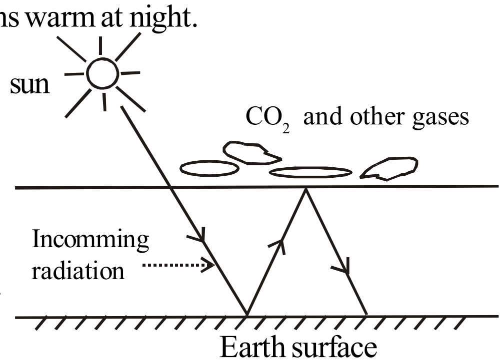
Mesosphere lies between 50 km to 80Km .The temperature of this region falls from 7^0 to -93^0C.

4. Ionosphere

This layer extends from a height of 80Km to 400 Km . Ionosphere contains free electrons and ions .These free electrons and ions are produced by radiation from the sun and other stars. Ionosphere can reflect the radio waves. Hence this layer is very useful for radio communication.

Green-House Effect

This is a phenomenon by which the earth's surface remains warm at night. Earth is heated by radiations from the sun. Inturn earth radiates infrared radiations to the space. This radiation (out going) of longer wave length is reflected by CO_2 and other gases . So that radiation (from earth) can't escape from earth's atmosphere. Thus the temperature at earth's surface increases. This phenomenon is called Green house effect.
In the absence of atmosphere there will be no green house effect. Hence average temperature of surface will be lowered.



Points to ponder.

1.Electromagnetic waves carry energy as they travel through space and this energy is shared equally by the electric and magnetic fields.

2. Electromagnetic waves transport momentum as well. When these waves strike a surface, a pressure is exerted on the surface. If total energy transferred to a surface in time t is U, total momentum delivered to this surface is p = U/c.

3. The electromagnetic waves interact with matter via their electric and magnetic fields which set in oscillation charges present in all matter. The detailed interaction and so the mechanism of absorption, scattering, etc., depend on the wavelength of the electromagnetic wave, and the nature of the atoms and molecules in the medium.

4. The basic difference between various types of electromagnetic waves lies in their wavelengths or frequencies since all of them travel through vacuum with the same speed. Consequently, the waves differ considerably in their mode of interaction with matter.

5.Infrared waves, with frequencies lower than those of visible light,vibrate not only the electrons, but entire atoms or molecules of a substance. This vibration increases the internal energy and consequently, the temperature of the substance. This is why infrared waves are often called heat waves.