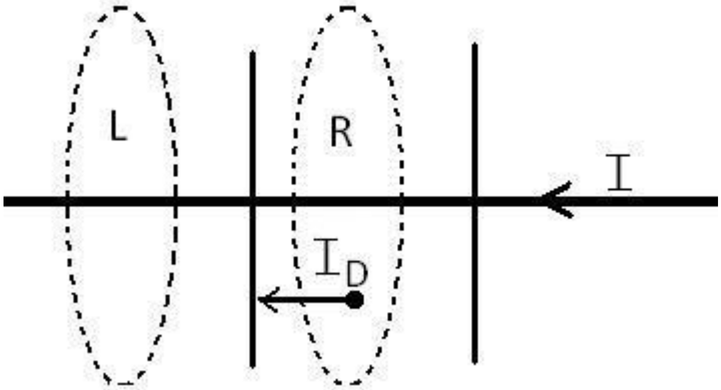
ELECTROMAGNETIC WAVES

DISPLACEMENT CURRENT

Current in capacitors
Consider the charging capacitor in the figure.



We have drawn two loops name as L which is outside the loop and Loop R which is in between the parallel plates of capacitor.
The capacitor is in a circuit that transfers charge (on a wire external to the capacitor) from the left plate to the right plate, charging the capacitor and increasing the electric field between its plates. The same current enters the right plate (say I) as leaves the left plate. Although current is flowing through the capacitor, no actual charge is transported through the vacuum between its plates.
Ampere's circuital is not applicable for loop L and we can find magnetic field at point P using Ampere's circuital law

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

Now if we consider an imaginary cylindrical surface. No conduction current enters cylinder surface *R*, while current *I* leaves through surface *L*. Thus Ampere's law is not applicable and magnetic field at point P must be zero. So we have a *contradiction*; calculated one way, there is a magnetic field at a point P; calculated another way, the magnetic field at P is zero.
Nonetheless, a magnetic field exists between the plates as though a current were present there as well.
For consistency of Ampere's Circuital law requires a displacement current $I_D = I$ to flow across surface *R*.
The explanation is that a *displacement current* I_D flows in the vacuum, and this current produces the magnetic field in the region between the plates according to Ampere's law
If Q is the charge on capacitor plate and area of plates of capacitor is A
Electric field between plates is

$$E = \frac{Q}{\varepsilon_0 A}$$

When capacitor is getting charged rate of change in electric field is

$$\frac{\partial E}{\partial t} = \frac{1}{\varepsilon_0 A}\frac{dQ}{dt}$$

$$\varepsilon_0 A \frac{\partial E}{\partial t} = I_D$$

Here I_D is called displacement current

In integral form

$$\varepsilon_0 \int \frac{\partial \vec{E}}{\partial t} \overrightarrow{da} = I_D$$

$$\varepsilon_0 \int \frac{d\phi_E}{dt} = I_D$$

This current does not have significance in the sense of being the motion of charges.

The generalization made by Maxwell then is the following. 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

Adding integral form of displacement current in Ampere's law we get

$$\oint \vec{B} \cdot \overrightarrow{dl} = \mu_0 I_C + \mu_0 \varepsilon_0 \int \frac{d\phi_E}{dt}$$

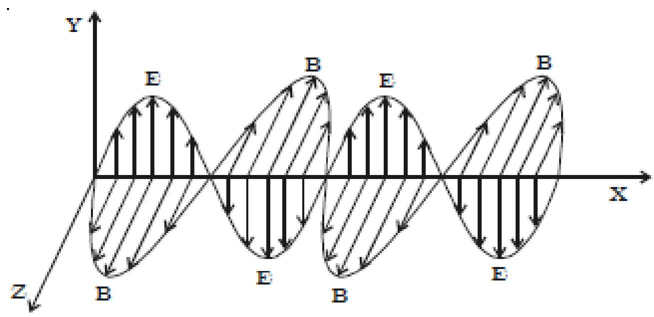
and is known as Ampere-Maxwell law.

Electromagnetic waves

According to Maxwell, an accelerated charge is a source of electromagnetic radiation.

In an electromagnetic wave, electric and magnetic field vectors are at right angles to each other and both are at right angles to the direction of propagation.

They possess the wave character and propagate through free space without any material medium. These waves are transverse in nature. Fig shows the variation of electric field E along Y direction and magnetic field B along Z direction and wave propagation in + X direction



According to Maxwell's theory, these electric and magnetic field do not come into existence instantaneously. In the region closer to the oscillating change, the phase difference between electric field **E** and Magnetic field **B** is π/2 and their magnitude quickly decreases as $1/r^3$ (where r = distance from source) these components are called *Inductive component.*

At larger distance **E** and **B** are in phase and the decrease in their magnitude is comparatively slower with distance, as per 1/r. These components are called radiated components

Characteristics of Electromagnetic waves

(1) Representation in form of equations:
Electromagnetic wave shown in figure at time t, the y component is E_Y of electric field given by equation $E_Y = E_0 \sin(\omega t - kx)$
In vector form **E** = E_Y**j** = [$E_0 \sin(\omega t - kx)$] **j**
Similarly Magnetic component is given as **B** =[B_0 ($\omega t - kx$)] **k**

(2) Relation between magnitude of **E** and **B** is E = Bc
Here c is velocity of light

(3) The velocity of electromagnetic waves in vacuum

$$c = \frac{1}{\sqrt{\varepsilon_0 \mu_0}}$$

The velocity of electromagnetic waves in medium

$$v = \frac{1}{\sqrt{\varepsilon \mu}}$$

Here ε = permittivity of the medium and μ = permeability of the medium

From definition of refractive index

$$n = \frac{c}{v}$$

$$n = \frac{\sqrt{\varepsilon \mu}}{\sqrt{\varepsilon_0 \mu_0}} = \sqrt{\frac{\varepsilon}{\varepsilon_0} \frac{\mu}{\mu_0}}$$

Since $\varepsilon_r = \frac{\varepsilon}{\varepsilon_0} = k$ dielectric constant of medium and relative permeability $\mu_r = \frac{\mu}{\mu_0}$

$$n = \sqrt{\varepsilon_r \mu_r}$$

(4) Electromagnetic waves are transverse in nature

(5) Electromagnetic waves posses energy and they carry energy from one place to the other .

(6) Electromagnetic waves exerts pressure on a surface when they are incident on it, called radiation pressure
If ΔU is the energy of electromagnetic waves incident on a surface of area A in time Δt , in direction normal to the surface and if all energy is absorbed then change in momentum

$$\Delta p = \frac{\Delta U}{c}$$

(7) Energy density of electromagnetic wave

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

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

$$I = \frac{Energy}{(time)(area)} = Power$$

If radiation is passing through unit area with velocity c then volume in one second = c
Thus energy volume = ρc from the value of ρ *we get*

$$I = \varepsilon_0 c E_{rms}^2$$

Similarly

$$I = \frac{cB_{rms}^2}{\mu_0}$$

(9) E ×B gives the direction of propagation of the electromagnetic wave

ELECTROMAGNETIC SPECTRUM

Sr. No.	Name	Source	Wavelength in (m)	Frequency range (Hz)
1	γ – rays	Radioactive nuclei, nuclear reactions	10^{-14} to 10^{-10}	3×10^{22} to $3\text{x } 10^{18}$
2	x – rays	High energy electrons suddenly stopped by a metal target	1×10^{-10} to 3×10^{-8}	3×10^{18} to 1×10^{16}
3	Ultra−violet	Atoms and molecules in electrical discharge	$6 \text{ x } 10^{-10}$ to 4×10^{-7}	$5 \text{ x } 10^{17}$ to 8×10^{14}
4	Visible light	incandescent solids, Fluorescent, lamps	$4 \text{ x } 10^{-7}$ to $8 \text{ x } 10^{-7}$	$8 \text{ x } 10^{14}$ to $4 \text{ x } 10^{14}$
5	Infra−red (IR)	molecules of hot bodies	$8 \text{ x } 10^{-7}$ to $3\text{x } 10^{-5}$	$4 \text{ x } 10^{14}$ to 1×10^{13}
6	Microwaves	Electronic device (Vacuum tube)	10^{-3} to 0.3	$3 \text{ x } 10^{11}$ to $1 \text{ x } 10^{9}$
7	Radio frequency wave	Charges accelerated through conducting wires	10 to 10^{4}	3 x 107 – 3 x 104

Electromagnetic spectrum covers a wide range of wavelengths (or) frequencies. The whole electromagnetic spectrum has been classified into different parts and sub parts, in order of increasing wavelength and type of excitation. All electromagnetic waves travel with the velocity of light. The physical properties of electromagnetic waves are determined by their wavelength and not by their method of excitation.

The overlapping in certain parts of the spectrum shows that the particular wave can be produced by different methods.

Uses of electromagnetic spectrum

The following are some of the uses of electromagnetic waves.

1. Radio waves : These waves are used in radio and television communication systems.

AM band is from 530 kHz to 1710 kHz.
Higher frequencies upto 54 MHz are used for short waves bands.
Television waves range from 54 MHz to 890 MHz.
FM band is from 88 MHz to 108 MHz.
Cellular phones use radio waves in ultra high frequency (UHF) band.

2. Microwaves : Due to their short wavelengths, they are used in radar communication system.

Microwave ovens are an interesting domestic application of these waves.

3. Infra red waves :

(i) Infrared lamps are used in physiotherapy.
(ii) Infrared photographs are used in weather forecasting.
(iii) As infrared radiations are not absorbed by air, thick fog, mist etc, they are used to take photograph of long distance objects.
(iv) Infra red absorption spectrum is used to study the molecular structure.

4. Visible light : Visible light emitted or reflected from objects around us provides information about the world. The wavelength range of visible light is 4000 Å to 8000 Å.

5. Ultra−violet radiations

(i) They are used to destroy the bacteria and for sterilizing surgical instruments.
(ii) These radiations are used in detection of forged documents, fingerprints in forensic laboratories.
(iii) They are used to preserve the food items.
(iv) They help to find the structure of atoms.

6. X rays :

(i) X rays are used as a diagnostic tool in medicine.
(ii) It is used to study the crystal structure in solids.

7. γ–rays : Study of γ rays gives useful information about the nuclear structure and it is used for treatment of cancer

Solved Numerical

Q) A 1000 W bulb is kept at the centre of a spherical surface and is at a distance of 10 m from the surface. Calculate the force acting on the surface of the sphere by the electromagnetic waves, along with E_0, B_0 and intensity I. Take the working efficiency of the bulb to be 2.5% and consider it as a point source, , calculate the energy density on the surface .

Solution:

The energy consumed every second by a 1000W bulb = 1000J

As the working efficiency of the bulb is equal to 2.5%, the energy radiated by the bulb per second

$$\Delta U = 1000 \times \frac{2.5}{100}$$
$$\therefore \Delta U = 25\, Js^{-1}$$

Considering, the bulb at the centre of the sphere, surface area of the sphere

A = $4\pi R^2$ = (4)(3.14)(10^2) = 1256 m^2

Intensity I

$$I = \frac{Energy}{(time)(area)} = \frac{25}{1256} = 0.02 Wm^{-2}$$
$$I = \varepsilon_0 c E_{rms}^2 = 0.02$$
$$\therefore E_{rms} = \left[\!\left[\frac{0.02}{8.85 \times 10^{-12} \times 3.0 \times 10^5}\right]\!\right]^{1/2} = 2.74\, Vm^{-1}$$

NOW

$$B_{rms} = \frac{E_{rms}}{c}$$
$$B_{rms} = \frac{2.74}{3.0 \times 10^8} = 9.13 \times 10^{-9} T$$
$$E_0 = \sqrt{2} E_{rms}$$
$$E_0 = 1.41 \times 2.74 = 3.86\, Vm^{-1}$$

$$B_0 = \sqrt{2} B_{rms}$$
$$B_0 = 1.41 \times 9.13 \times 10^{-9} = 1.29 \times 10^{-8}\, T$$

The total energy incident on the surface = 25J

∴ The momentum (Δp) imparted to the surface in one second (= force)

$$\Delta p = \frac{\Delta U}{c} = F = \frac{25}{3 \times 10^8} = 8.33 \times 10^{-8} N$$

From I = ρc, energy density

$$\rho = \frac{I}{c} = \frac{0.02}{3 \times 10^8} = 6.67 \times 10^{-11} Jm^{-3}$$

Q) The maximum electric field at a distance of 10 m from an isotropic point source of light is 3.0 V/m. Calculate (a) the maximum value of magnetic field (b) average intensity of the light at that place and (c) the power of the source
$\varepsilon_o = 8.854 \times 10^{-12}\ C^2N^{-2}\ m^{-2}$

Solution
(a)maximum value of magnetic field
E = Bc

$$B = \frac{E}{c} = \frac{3.0}{3.0 \times 10^8} = 10^{-8}\text{T}$$

(b) average intensity of the light at that place
From formula

$$I = \varepsilon_0 c E_{rms}^2 = \varepsilon_0 c \times \frac{E_0^2}{2}$$

$$I = 8.854 \times 10^{-12} \times 3.0 \times 10^8 \times \frac{(3.0)^2}{2}$$

$$I = 1.195 \times 10^{-2}\ wm^{-2}$$

(c) Power
Power = I × Area = I ×4πr^2
Power = 1.195×10^{-2}×4×3.14×(10)^2 = 15 w

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