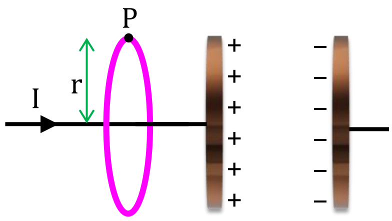
04 Electromagnetic Waves

We have seen that a magnetic field changing with time gives rise to an electric field. Is the converse also true? Does an electric field changing with time give rise to a magnetic field?
James Clerk Maxwell (1831-1879), argued that this was indeed the case – not only an electric current but also a time-varying electric field generates magnetic field. While applying the Ampere's circuital law to find magnetic field at a point outside a capacitor connected to a time-varying current, Maxwell noticed an inconsistency in the Ampere's circuital law. He suggested the existence of an additional current, called by him, the displacement current to remove this inconsistency.
To see how a changing electric field gives rise to a magnetic field, let us consider the process of charging of a capacitor.

Case-1

Question: Calculate Magnetic Field at P



Solution: For this, we consider a plane circular loop of radius r whose plane is perpendicular to the direction of the current-carrying wire, and which is centred symmetrically with respect to the wire

Using Ampere's Law

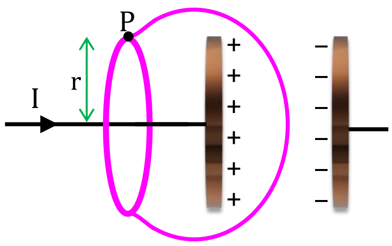
$$\oint \vec{B}.d\vec{l} = \mu_0 I_{enc}$$

$$B_P\,(2\pi r) = \mu_0 I$$

$$B_P = \frac{\mu_0 I}{2\pi R}$$

Case-2

Question: Calculate Magnetic Field at P



Solution: Here we consider a different surface, which has the same boundary. This is a pot like surface which nowhere touches the current, but has its bottom between the capacitor plates.

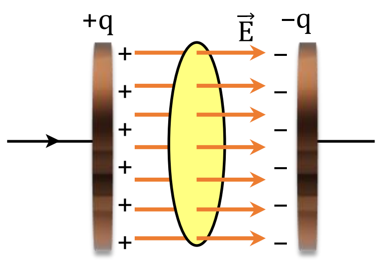
Using Ampere's Law

$$\oint \vec{B}.d\vec{l} = \mu_0 I_{enc}$$

$$B_P\,(2\pi r) = \mu_0(0) \quad (\because \text{ No current passes through the surface})$$

$$B_P = 0$$

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. This shows the inconsistency in ampere circuital law.
But what is the reason for this inconsistency? We can easily solve this problem by considering the following situation.



Electric field between the plates

$$E = \frac{q}{A\epsilon_0}$$

Electric flux through shaded area

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

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

Since charge q is varying w.r.t. time,

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

$$\frac{dq}{dt} = \epsilon_0 \frac{d\phi_E}{dt} \Rightarrow i_d = \frac{d\phi_E}{dt}$$

Maxwell defined $i_d = \epsilon_0 \frac{d\phi_E}{dt}$ as Displacement Current.

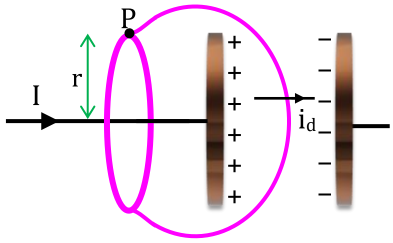
So, this is the solution of inconsistency that we observed. So, in Case2

Using Ampere's Law

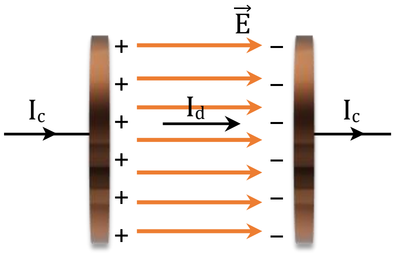
$$\oint \vec{B}.d\vec{l} = \mu_0 I_{enc}$$

$B_P (2\pi r) = \mu_0(i_d)$ $(\because$ i_d passes through the surface)

$$B_P = \frac{\mu_0 i_d}{2\pi R}$$



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.



Conduction current (I_c)	Displacement current (I_d)
• Due to flow of charge in the conducting wire. • Denoted by I_C. $I_c = \frac{dq}{dt}$	• Due to variable electric field between plates of charging capacitor. • Denoted by I_d. $i_d = \epsilon_0 \frac{d\phi_E}{dt}$

Hence, total current is defined as $I = I_C + I_d$

So, Ampere's Circuital Law can be written as –

$$\oint \vec{B}.d\vec{l} = \mu_0 (I_c + I_d) \quad \text{[Also known as Ampere Maxwell's Law]}$$

Displacement current also solved the current continuity problem

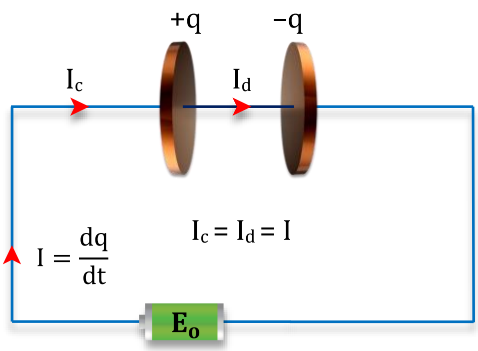
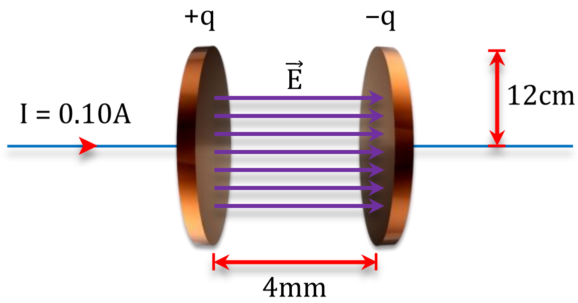


Illustration 1

Figure shows a capacitor made of two circular plates each of radius 12 cm and separated by 4.0 mm. The capacitor is being charged by an external source (not shown in the figure). The charging current is constant and is equal to 0.10 A. Find



(a) Capacitance

(b) Rate of change of potential difference between the plates?

(c) Displacement current across the plates?

Solution:

(a) Area of one of the plates.

$A = \pi(12 \times 10^{-2}\text{ m})^2$

Distance between the plates, $d = 4.0\text{ mm} = 4 \times 10^{-3}\text{ m}$

Capacitance of the capacitor, $C = \varepsilon_0 A/d$

$$C = \left(8.85 \times 10^{-12}\frac{C^2}{N - m^2}\right) \times \frac{\pi(12 \times 10^{-2}\text{m})^2}{4 \times 10^{-3}\text{m}}$$

$C = 100 \times 10^{-12}\text{ F} = 100\text{ pF}$

Charging current, $I = \frac{dQ}{dt} = \frac{d}{dt}(CV)$ or $I = C\frac{dV}{dt}$ or $\frac{dV}{dt} = \frac{I}{C}$

(b) Rate of change of potential difference $= \frac{dV}{dt} = \frac{I}{C}$

$$\frac{dV}{dt} = \frac{0.10\text{A}}{100 \times 10^{-12}\text{F}} = 1 \times 10^9\text{ V/s}$$

(c) Displacement current $I_d = \varepsilon_0 A\left(\frac{dE}{dt}\right)$

For a parallel-plate capacitor,

$$E = \frac{\sigma}{\epsilon_0} = \frac{Q/A}{\epsilon_0} = \frac{Q}{\epsilon_0 A}$$

Where σ is surface density of charge.

$$I_d = \varepsilon_0 A \times \left(\frac{d}{dt}\left(\frac{Q}{\varepsilon_0 A}\right)\right)$$

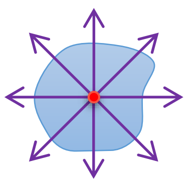
$$I_d = \varepsilon_0 A \times \frac{1}{\varepsilon_0 A}\frac{dQ}{dt} = \frac{dQ}{dt} = I_c \Rightarrow \text{So } I_d = I_c = 0.10\text{ A}$$

Maxwell's Equations and Properties of Electromagnetic Waves

Maxwell's Equations

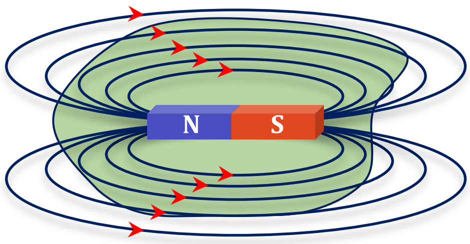
1. Gauss' Law in Electrostatics

$$\oint \vec{E} \cdot d\vec{A} = \frac{Q_{en}}{\epsilon_0}$$



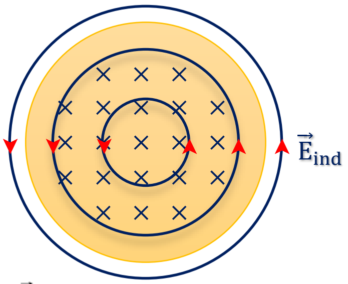
2. Gauss' Law in Magnetism

$$\oint \vec{B}\cdot d\vec{A} = 0$$



3. Maxwell-Faraday's Law

$$\oint \vec{E}\cdot d\vec{l} = -\frac{d\phi_B}{dt}$$



$\vec{B}$ changing with time

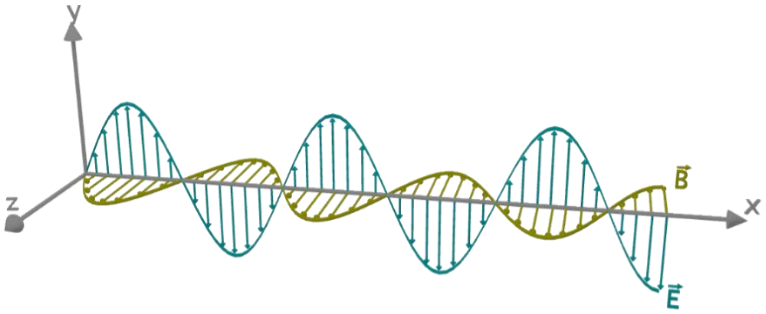
4. Ampere – Maxwell Law

$$\oint \vec{B}\cdot d\vec{l} = \mu_0\left(I_c + \epsilon_0 \frac{d\phi_E}{dt}\right)$$

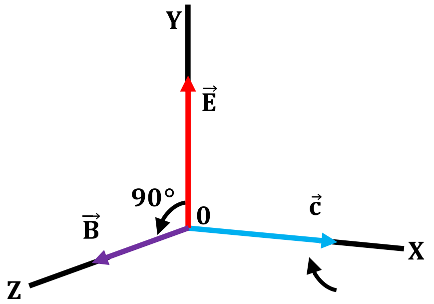
Charge	Generates	
at rest	$\vec{E}$	$\vec{E}$ = Electric Field
Uniform Motion	$\vec{E}, \vec{B}$	$\vec{B}$ = Magnetic Field
Accelerated Motion	$\vec{E}, \vec{B}$, EMW	EMW = Electromagnetic Waves

Electromagnetic Waves

Electromagnetic waves consist of sinusoidally time varying Electric and Magnetic field. Electric and magnetic fields oscillate sinusoidally in perpendicular planes as well as the direction the propagation of wave so, EMW are transverse in nature.



Properties of Electromagnetic Waves



Direction of propagation = Direction of $\vec{E} \times \vec{B}$ with help of right hand rule

- EMW are non-mechanical in nature, and they don't require medium to transfer energy and momentum.
- The electric and magnetic fields variations are in phase.
- The direction of propagation of wave is along $\vec{E} \times \vec{B}$

  For Example,

  If, $\vec{E} = E\hat{j}$ and $\vec{B} = B\hat{k}$

  then, wave moves along $\rightarrow$ $\hat{j} \times k = \hat{i}$
- The electric and magnetic fields of a sinusoidal electromagnetic wave propagating in the positive x-direction can be written as

  $E_Y = E_0 \sin(kx - \omega t)$

  $B_Z = B_0 \sin(kx - \omega t)$

  here,

  Angular frequency, $\omega = 2\pi f$

  Wave number, $k = \dfrac{2\pi}{\lambda}$

  Speed of wave $v = \dfrac{\omega}{k}$
- The magnitude of the electric and the magnetic fields in an electromagnetic wave are related as $\dfrac{E}{B} = c$
- $\mu_0 \in_0 = \dfrac{\mu_0}{4\pi}(4\pi \in_0) = \dfrac{10^{-7}}{9\times 10^9} = \dfrac{1}{9\times 10^{16}} = \dfrac{1}{(3\times 10^8)^2} = \dfrac{1}{c^2}$

  So, in vacuum, speed of EMW is $c = \dfrac{1}{\sqrt{\mu_0 \varepsilon_0}} = 3\times 10^8\ \text{m/s}$

  In medium : $v = \dfrac{1}{\sqrt{\mu \in}} = \dfrac{1}{\sqrt{(\mu_0\mu_r)(\varepsilon_0\varepsilon_r)}} = \dfrac{1}{\sqrt{(\mu_0\varepsilon_0)}}\dfrac{1}{\sqrt{(\mu_r\varepsilon_r)}} = \dfrac{c}{\sqrt{\mu_r\varepsilon_r}}$
- Refractive index, $n = \dfrac{c}{v} = \sqrt{(\mu_r\varepsilon_r)}$

Note: Like any other wave, $c = f\lambda$ is applicable for EMW as well.

Illustration 2

In a plane electromagnetic wave, the electric field oscillates sinusoidally at a frequency of 2.0×10^{10} Hz and amplitude 48 V/m.

(a) What is the wavelength of the wave? (b) What is the amplitude of the oscillating magnetic field?

Solution:

We are given that;

$E_0 = 48$ V/m, $f = 2.0 \times 10^{10}$ Hz and $c = 3 \times 10^8$ V/m

(a) Wavelengths of the wave,

$$\lambda = \frac{c}{f} = \frac{3\times 10^8\ \text{m/s}}{2.0\times 10^{10}\ \text{s}^{-1}} = 1.5 \times 10^{-2}\ \text{m}$$

(b) Amplitude of the oscillating magnetic field,

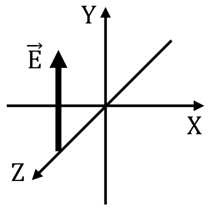
$$B_0 = \frac{E_0}{c} = \frac{48\ \text{V/m}}{3\times 10^8\ \text{m/s}} = 1.6 \times 10^{-7}\ \text{T}$$

Illustration 3
Electromagnetic waves travel in a medium which has relative permeability 1.3 and relative permittivity 2.14. Then the speed of the electromagnetic wave in the medium will be

Solution:

$$v = \frac{c}{\sqrt{\mu_r \varepsilon_r}} = \frac{3\times10^8}{\sqrt{1.3\times2.14}} = 1.8\times10^8\,m/s$$

Illustration 4
Figure shows the direction of electric field of an EMW at a certain point and at certain instant. The wave is transporting energy in the negative Z direction. What is the direction of the magnetic field of the wave at that point and instant?



Solution:

The direction of EM waves is given by the direction of $\vec{E}\times\vec{B} = (\hat{j}\times n) = -k$

That is $\hat{n} \rightarrow \hat{i}$ (direction of $\vec{B}$)

Illustration 5
Radio receiver receive a message at 300m band, If the available inductance is 1 mH, then calculate required capacitance.

Solution:

Radio receive EM waves (velocity of EM waves c = 3 x 10^8 m/s)

$\therefore \quad c = f\lambda \quad \Rightarrow \quad f = \frac{3\times10^8}{300} = 10^6$ Hz

Now $\quad f = \frac{1}{2\pi\sqrt{LC}} = 1\times10^6 \quad \Rightarrow \quad C = \frac{1}{4\pi^2\times10^{-3}\times10^{12}} = 25$ pF

Energy Density
Total Energy Density = Energy Density in Electric Field + Energy Density in Magnetic Field

$$U_T = \frac{1}{2}\varepsilon_0 E^2 + \frac{1}{2}\frac{B^2}{\mu_0}$$

Where, $E = E_0\sin(kx-\omega t)$

$B = B_0\sin(kx-\omega t)$

we know that,

$$c = \frac{E}{B} \;\&\; c = \frac{1}{\sqrt{\mu_0\varepsilon_0}} \Rightarrow \frac{E^2}{B^2} = \frac{1}{\mu_0\varepsilon_0}$$

$$U_E = \frac{1}{2}\varepsilon_0 E^2 = \frac{1}{2}\varepsilon_0\left(\frac{B^2}{\mu_0\varepsilon_0}\right) = \frac{1}{2}\frac{B^2}{\mu_0} = U_B$$

hence,

$U_E = U_B$

Total energy density of EMW is distributed equally in Electric and Magnetic Fields.

So, total energy density of an EMW can be written as-

$$U_T = 2U_E = 2U_B$$

$$U_T = \varepsilon_0 E^2 = \frac{B^2}{\mu_0}$$

where, $E = E_0\sin(kx-\omega t)$

$B = B_0\sin(kx-\omega t)$

Average Energy Density

Average Energy Density of Electric Field

$$U_E = \frac{1}{2}\varepsilon_0 E^2$$

$$< U_E > = \frac{1}{2}\varepsilon_0 < E >^2$$

Here

$$E = E_0 \sin(kx - \omega t)$$

$$< E^2 > = E_0^2 < \sin^2(kx - \omega t) >$$

$$< E^2 > = \frac{E_0^2}{2} \quad < \sin^2(kx - \omega t) > = \frac{1}{2}$$

$$< E > = \frac{E_0}{\sqrt{2}}$$

So average energy density of electric field

$$< U_E > = \frac{1}{2}\varepsilon_0\left(\frac{E_0^2}{2}\right) = \frac{1}{4}\varepsilon_0 E_0^2$$

and average energy density of magnetic field

$$< U_B > = \frac{1}{2}\frac{1}{\mu_0}\left(\frac{B_0^2}{2}\right) = \frac{1}{4}\frac{B_0^2}{\mu_0}$$

and average energy density of electromagnetic wave

$$< U_T > = \frac{1}{2}\varepsilon_0 E_0^2 = \frac{1}{2}\frac{B_0^2}{\mu_0}$$

Unit: J/m^3

Here, E_o & B_0 are peak values.

Illustration 6

In a plane electromagnetic wave, the electric field oscillates sinusoidally at a frequency of 2.0×10^{10} Hz and amplitude 48 V/m.

Find the total average energy density of the electromagnetic field of the wave.

Solution:

Total average energy density,

$$< U_T > = \frac{1}{2}\varepsilon_0 E_0^2$$

$$< U_T > = \frac{1}{2}(8.85 \times 10^{-12})(48)^2 \ J/m^3$$

$$< U_T > = 1.0 \times 10^{-8} \ J/m^3$$

Illustration 7

In an electromagnetic wave, the amplitude of electric field is 1 V/m. The frequency of wave is 5×10^{14} Hz. The wave is propagating along z-axis. The average energy density of electric field, in Joule/m^3, will be –

Solution:

Average energy density is given by

$$< u_E > = \frac{1}{4}\varepsilon_o E_o^2 \quad \Rightarrow \quad u_E = \frac{1}{4} \times 8.85 \times 10^{-12} \times (1)^2 \quad \Rightarrow \quad u_E = 2.2 \times 10^{-12} \ J/m^3$$

Illustration 8

A plane light wave in the visible region is moving along the Z-direction. The frequency of the wave is 0.5×10^{15} Hz and the electric field at any point is varying sinusoidally with time with an amplitude of 1 V/m. Calculate the average energy densities of the electric and magnetic fields.

Solution:

Total average energy density (due to both electric and magnetic fields)

$$< U_T > = \frac{1}{2}\varepsilon_0 E_0^2 = \frac{1}{2}\ (8.85 \times 10^{-12})\ (1)^2 = 4.42 \times 10^{-12}\ J/m^3$$

Since the energy is shared equally by the electric and magnetic fields,

average energy density of the electric field

$$< U_E > = \frac{1}{2}(4.42 \times 10^{-12}\ J/m^3) = 2.21 \times 10^{-12}\ J/m^3$$

average energy density of the magnetic field

$$< U_B > = \frac{1}{2}(4.42 \times 10^{-12}\ J/m^3) = 2.21 \times 10^{-12}\ J/m^3$$

Poynting Vector and Intensity of EMW

Poynting Vector: The total energy flowing perpendicularly per second per unit area into the surface in free space is called a Poynting Vector.

It also represents power transferred per unit area.

Direction : along direction of wave propagation

SI unit : J/s-m^2 or W/m^2

Mathematically, it is given by-

$$\vec{S} = \frac{1}{\mu_0}(\vec{E} \times \vec{B})$$

Since $\vec{E} \perp \vec{B}$

$$S = \frac{EB}{\mu_0} = \frac{E^2}{c\mu_0} = \frac{B^2 c}{\mu_0}$$

$$S = \frac{E^2}{c\mu_0} \qquad \left(\because B = \frac{E}{c}\right)$$

$$S = \frac{B^2 c}{\mu_0} \qquad (\because E = cB)$$

Intensity

It represents the average time rate at which energy flows through a unit surface area perpendicular to the direction of the propagation of the wave. In other words, it is the average value of poynting vector over one cycle.

It also represents average power transferred per unit area.

Direction : Along direction of wave propagation

SI unit : J/s-m^2 or W/m^2

$$I = \langle S \rangle = C\langle U \rangle = C\frac{1}{2}\varepsilon_0 E_o^2 = C\frac{B_o^2}{2\mu_o}$$

Momentum of Electromagnetic Waves and Radiation Pressure

Momentum of Electromagnetic Waves

EM wave during its propagation has linear momentum associated with it. The linear momentum carried by the portion of wave having energy U is given by $p = \frac{U}{C}$

Radiation Pressure

The mechanical pressure exerted upon any surface due to the exchange of momentum between the surface and the electromagnetic wave.

$$P_R = \frac{F}{A}$$

Transfer of Momentum and Radiation Pressure

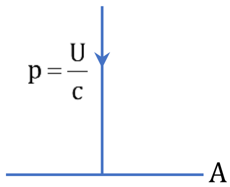
Case-1:

If section of an EMW having energy U strikes a surface of surface area A, then if the surface is perfect absorber and incidence is normal then momentum transferred to the surface,

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

Force exerted on the surface by EMW

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



Perfectly Absorbing Surface

Radiation pressure, $P_R = \frac{F}{A} = \frac{U}{c\Delta t A}$

$\because$ Intensity, $I = \frac{U}{A\Delta t}$

So, Radiation Pressure, $P_R = \frac{I}{c}$

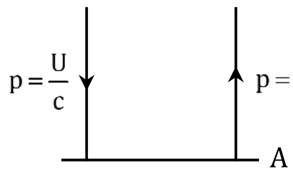
Case-2:

If section of an EMW having energy U strikes a surface of surface area A, then if the surface is perfect reflector and incidence is normal then momentum transferred to the surface,

$$\Delta p = \frac{2U}{c}$$

Force exerted on the surface by EMW

$$F = \frac{\Delta p}{\Delta t} = \frac{2U}{c\Delta t}$$



Perfectly Reflecting Surface

Radiation pressure, $P_R = \frac{F}{A} = \frac{2U}{c\Delta t A}$

$\because$ Intensity, $I = \frac{U}{A\Delta t}$

So, radiation pressure $P_R = \frac{2I}{c}$

Case-3:

For oblique incidence

Perfectly Absorbing	Perfectly Reflecting
Radiation Pressure, $P_R = \frac{I}{c}\cos^2\theta$ where θ is angle of incidence	Radiation Pressure, $P_R = \frac{2I}{c}\cos^2\theta$ where θ is angle of incidence

Electromagnetic spectrum

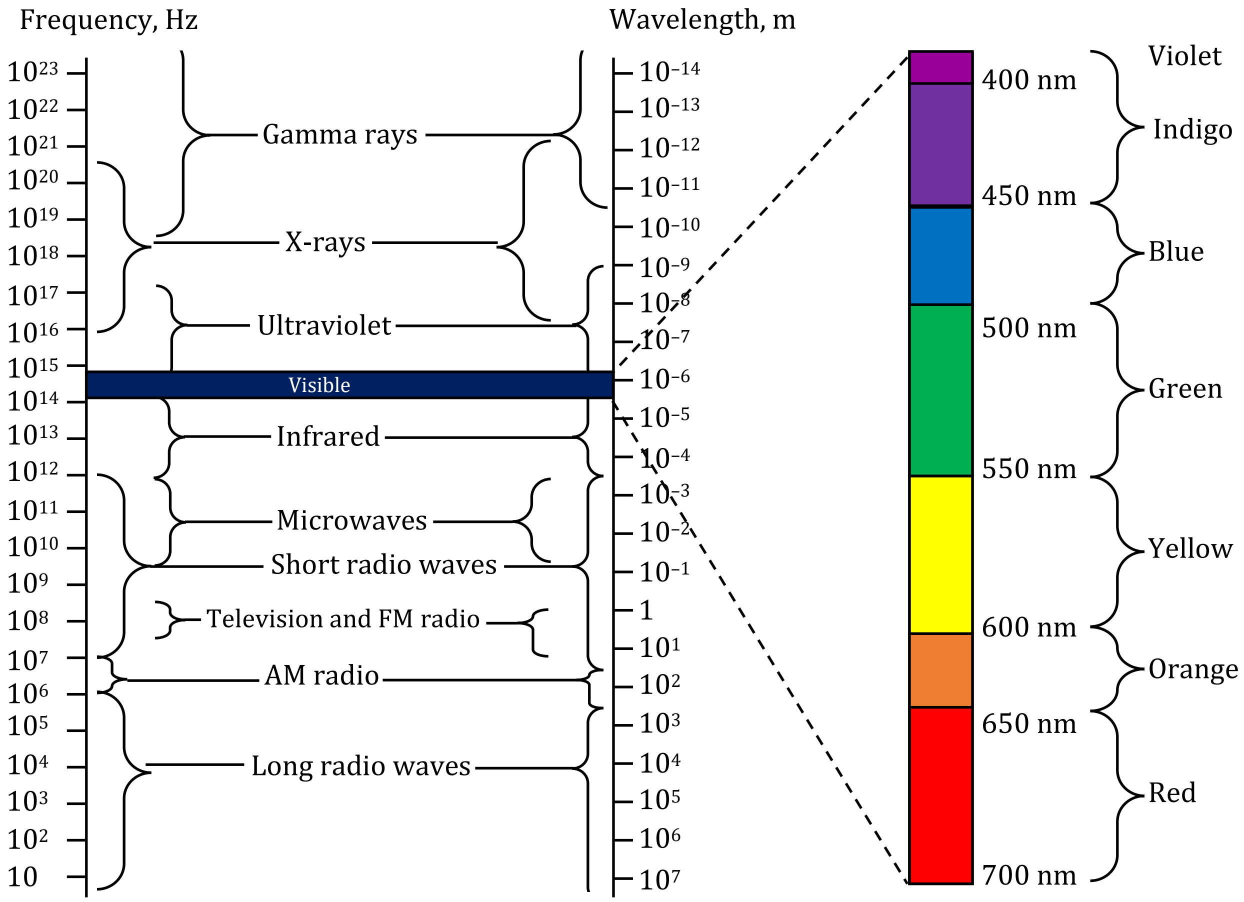
Electromagnetic spectrum in simple terms is defined as the range of all types of electromagnetic radiation. We shall learn about the concept in detail and understand all its underlying aspects in this lesson.

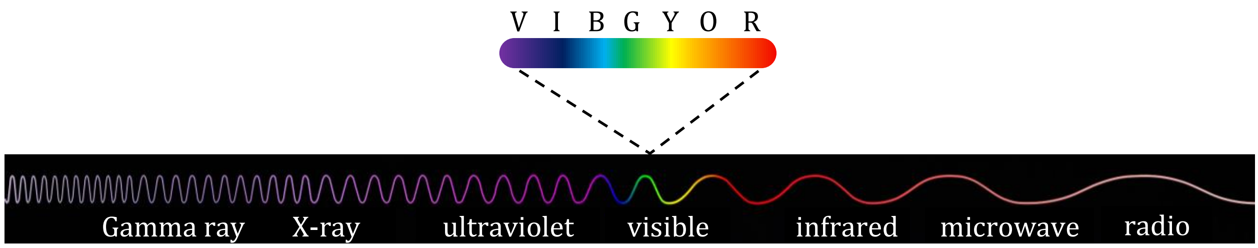
The electromagnetic spectrum is a range of frequencies, wavelengths and photon energies covering frequencies from above 1 Hz to below 10^{25} Hz corresponding to wavelengths which are a few kilometres to a fraction of the size of an atomic nucleus in the spectrum of electromagnetic waves. Generally, in a vacuum electromagnetic wave tend to travel at speeds which is similar to that of light. However, they do so at a wide range of wavelengths, frequencies, and photon energies.

The electromagnetic spectrum consists of a span of all electromagnetic radiation which further contains many subranges which are commonly referred to as portions. These can be further classified as infra-red radiation, visible light or ultraviolet radiation.

Electromagnetic Waves in Electromagnetic Spectrum

The entire range (electromagnetic spectrum) is given by radio waves, microwaves, infrared radiation, visible light, ultra-violet radiation, X-rays, gamma rays and cosmic rays in the increasing order of frequency and decreasing order of wavelength. The type of radiation and their frequency and wavelength ranges are as follows:





We see the uses of the electromagnetic waves in our daily life as :

Type	Wave length range	Production	Application
Gamma rays	[< 10^{-3} nm]	Radioactive decay of the nucleus	Gamma rays used in medicine to destroy cancer cells
X-rays	[10^{-3}nm to 1nm]	X-ray tubes or inner shell electrons	treatment of certain types of cancer
ultraviolet rays	[1nm to 400nm]	Inner shell electrons in atoms moving from one energy level to a lower level energy level to a lower level	LASIK eye surgery, Water purifiers
Visible rays	[400nm to 700nm]	Electrons in atoms emit light when they move from one energy level to a lower energy level	part of the electromagnetic spectrum detected by the human eye.
Infrared rays	[700nm to 1mm]	Vibration of atoms and molecules	Remote of TV, video recorders
Micro wave	[1mm to 0.1m]	Klystron valve or magnetron valve	radar systems, microwave ovens
Radio wave	[> 0.1m]	Rapid acceleration and deaccelerations of electrons in aerials	Radio communication like TV, radio, mobile communication etc.

Radio
A radio basically captures radio waves that are transmitted by radio stations. Radio waves can also be emitted by gases and stars in space. Radio waves are mainly used for TV/mobile communication.

Microwave
This type of radiation is found in microwaves and helps in cooking at home/office. It is also used by astronomers to determine and understand the structure of nearby galaxies and stars.

Infrared
It is used widely in night vision goggles. These devices can read and capture the infrared light emitted by our skin and objects with heat. In space, infrared light helps to map the interstellar dust.

X-ray
X-rays can be used in many instances. For example, a doctor can use an x-ray machine to take an image of our bone or teeth. Airport security personnel use it to see through and check bags. X-rays are also given out by hot gases in the universe.

Gamma-ray
It has a wide application in the medical field. Gamma-ray imaging is used to see inside our bodies. Interestingly, the universe is the biggest gamma-ray generator of all.

Ultraviolet
Sun is the main source of ultraviolet radiation. It causes skin tanning and burns. Hot materials that are in space also emit UV radiations.

Visible
Visible light can be detected by our eyes. Light bulbs, stars, etc. emits visible light.

Some important wireless communication bands

Frequency band	Service
540-1600 kHz	Medium wave AM band
3-30 MHz	Shortwave AM band
88-108 MHz	FM broadcast
54-890 MHz	TV Waves
840-935 MHz	Cellular Mobile radio

Illustration 9
A point source of electromagnetic radiation has an average power output of 800W. The maximum value of electric field at a distance 3.5 m from the source will be –

Solution:

Intensity of electromagnetic wave given is by $I = \frac{P_{av}}{4\pi r^2} = C\frac{1}{2}\varepsilon_o E_o^2$

$$E_o = \sqrt{\frac{P_{avg}}{2\pi r^2 \varepsilon_o \times C}} = \sqrt{\frac{800}{2\times3.14\times(3.5)^2\times8.85\times10^{-12}\times3\times10^8}}$$

$$= \sqrt{\frac{800\times10^4}{2042.49}} = \sqrt{3916.7} = 62.58 V/m$$

Illustration 10
The sun delivers 10^4 W/m^2 of electromagnetic flux to the earth's surface. The total power that is incident on a roof of dimensions (10 × 10) m^2 will be

Solution:

Total power = electromagnetic flux × area = 10^4 × (10 × 10) = 10^6 W

Illustration 11
A flood light is covered with a filter that transmits red light. The electric field of the emerging beam is represented by a sinusoidal plane wave

$E_x = 36 \sin(1.20 \times 10^7 z - 3.6 \times 10^{15} t)$ V/m

The average intensity of beam in watt/metre^2 will be

Solution:

$$I_{avg} = \frac{1}{2}\varepsilon_0 E_0^2 \times c = \frac{1}{2}\times8.85\times10^{-12}\times(36)^2\times3\times10^8 = 1.719 \ \ W/m^2$$

Illustration 12
The decreasing order of wavelength of infrared, microwave, ultraviolet and gamma rays is

Solution:

Decreasing order of wavelength of various rays:

Microwaves > Infrared > Ultraviolet > Gamma rays

Illustration 13
The energy of the electromagnetic waves is of the order of 15 keV. To which part of the spectrum does it belong?

Solution:

E = 15 keV

$$\lambda = \frac{hc}{E} = \frac{6.6\times10^{-19}\times3\times10^8}{15\times10^6\times1.6\times10^{-19}}$$

$$\lambda = 0.8\,\text{Å} \approx 1\,\text{Å}$$

This wavelength belongs to X-rays

Illustration 14
A plane electromagnetic wave of intensity of 10 W/m^2 strikes a small mirror of area 20 cm^2, held perpendicular to the approaching wave. Find the radiation force on the mirror.

Solution:

Radiation force = (Radiation pressure) (Area)

$$= \left(\frac{2I}{c}\right)(A)$$

$$= \frac{2\times10\times20\times10^{-4}}{3\times10^8}$$

$= 1.33 \times 10^{-10}$ N