Class 12th Physics Chapter 8 Electromagnetic Waves Revision Notes & Important Question (www.free-education.in)

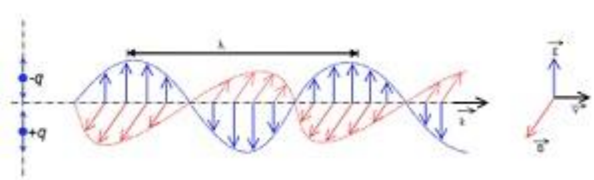
Introduction

- **We will discuss about electromagnetic waves, their properties and characteristics, and also their practical uses in our day-to-day life.**
- **One of the most important applications of electromagnetic wavesis in communication.**
- **Some of the important applications of electromagnetic waves are:-**

1. **We are able to see everything around us because of electromagnetic waves.**
2. **It helps in aircraft navigation and helps the pilot for the smooth take-off and landing of aeroplanes.It also helps to calculate the speed of the aeroplane.**
3. **In the medical field it has got very important applications. For example: - In laser eye surgery,in x-rays.**
4. **In radio and television broadcasting signals.These signals are transmitted by electromagnetic waves.**
5. **Electromagnetic waves helps in determining the speed of the passing vehicles.**
6. **They are used in electronic appliances like T.V. remotes,remote cars,LED TV,microwave ovens etc.**
7. **Voice transmission in mobile phones is possible because of electromagnetic waves.**

What are Electromagnetic Waves?

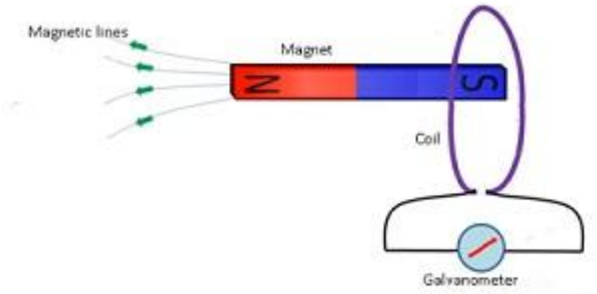
- **Electromagnetic (EM) waves are the waves which are related toboth electricity and magnetism.**
- **Electromagnetic (EM) waves are the waves which are coupled time varying electric and magnetic fields that propagate in space.**
- **Waves associated with electricity and magnetism and as they are waves so they willpropagate in the space.**
- **When the electric and magnetic fieldscombinetogether and whenthey are varying with time they both will give rise to electromagnetic waves.**
- **Electromagnetic equations emerged from Maxwell's equations.**
- **Maxwell found these EM waves have so many special properties which can be used for many practical purposes.**
- **Time varying electric field + Time varying magnetic field = Electromagnetic waves.**



Maxwell's Experiments

- **Maxwell proposed that the time varying electric field can generate magnetic field.**
- **Time varying magnetic field generates electric field (Faraday-Lenz law).**

1. **According to <u>Faraday Lenz law</u> an emf is induced in the circuit whenever the amount of magnetic flux linked with a circuit changes.**
2. **As a result electric current gets generated in the circuit which has an electric field associated with it.**



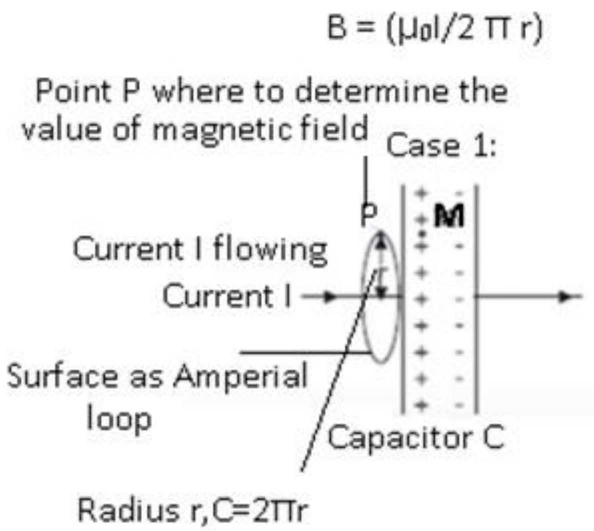
- **According to Maxwell if Faraday's law is true then the vice-versa should also be true, i.e. a time varying electric field should also be able to generate amagnetic field.**
- **According to Ampere's Circuital law, the line integral of magnetic field over the length element is equal to μ_0 times the total current passing through the surface $\int dl = \mu_0 I$**
- **According to Maxwell there was some <u>inconsistency</u> in the Ampere's circuital law.**
- **This means Ampere's circuital law was correct for some cases but not correct for some.**
- **Maxwell took different scenarios i.e. he took a capacitor and tried to calculate magnetic field at a specific point in a piece of a capacitor.**
- **Point P as shown in the figure is where he determined the value of B, assuming some current I is flowing through the circuit.**
- **He considered 3 different amperial loops as shown in the figs.**
- **Ampere's circuital law should be same for all the 3 setups.**

Case 1: Considered a surface of radius r & dl is the circumference of the surface, then from Ampere's circuital law

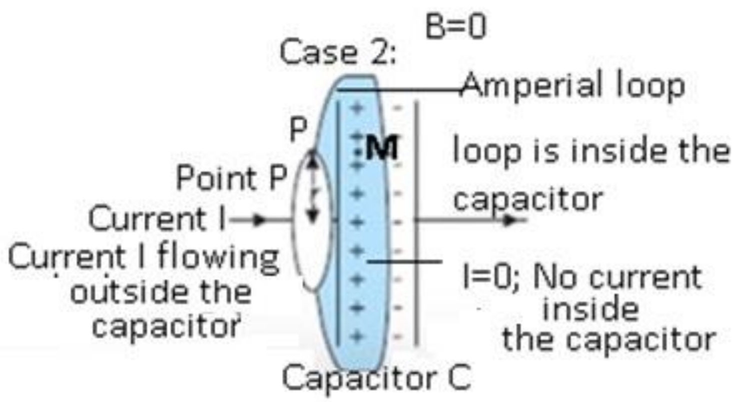
$\int B.dl = \mu_0 I$

or $B(2\pi r) = \mu_0 I$

or $B = \mu_0 I / 2\pi r$

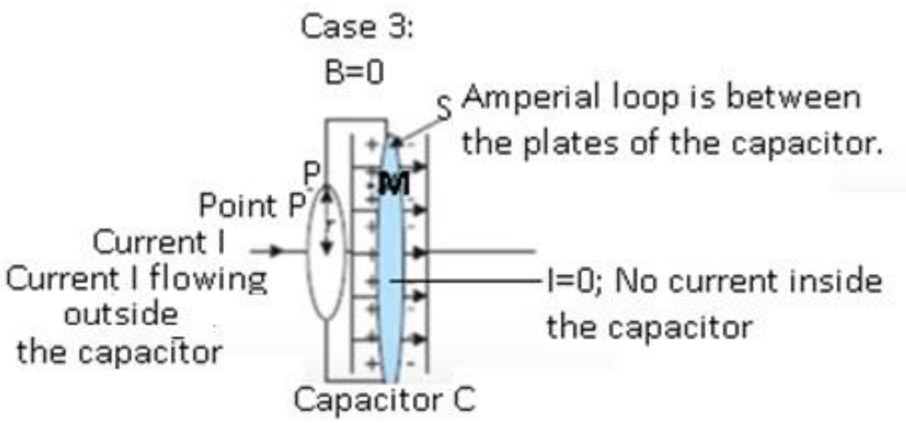


Case 2 : Considering a surface like a box & its lid is open and applying the Ampere's circuital law
$\int B.dl = \mu_0 I$



As there is no current flowing inside the capacitr, therefore I = 0
Or $\int B.dl = 0$

Case 3: Considering the surface between 2 plates of the capacitor, in this case also I=0, so B=0

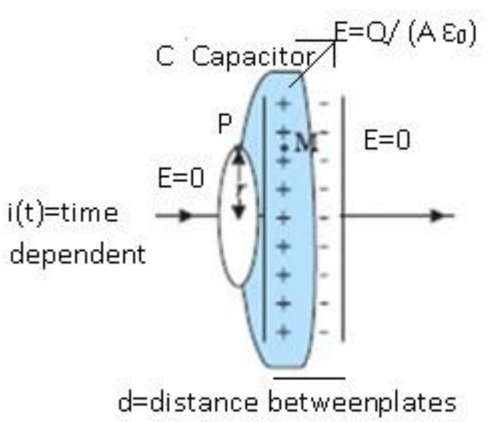


- At the same point but with different amperial surfaces the value of magnetic field is not same.They are different for the same point.
- Maxwell suggested that there are some gaps in the Ampere's circuital law.
- He corrected the Ampere's circuital law. And he made Ampere's circuital law consistent in all the scenarios.

Maxwell's correction to Ampere's law

- Ampere's law states that "the line integral of resultant magnetic field along a closed plane curve is equal to μ_0 time the total current crossing the area bounded by the closed curve provided the electric field inside the loop remains constant".
- Ampere's law is true only for steady currents.
- Maxwell found the shortcoming in Ampere's law and he modified Ampere's law to include time-varying electric fields.
- For Ampere's circuital law to be correct Maxwell assumed that there hasto be some current existing between the plates of the capacitor.
- Outside the capacitor current was due to the flow of electrons.
- There was no conduction of charges between the plates of the capacitor.
- According to Maxwell between the plates of the capacitor there is an electric field which is directed from positive plate to the negative plate.
  - Magnitude of the electric field E =(V/d)
    - Where V=potential difference between the plates, d = distance between the plates.
  - E = (Q/Cd)
    - where Q=charge on the plates of the capacitor,Capacitance of the capacitor=C
  - =>= $(Q/ (A\varepsilon_0 d/d))$where A =area of the capacitor.
  - $E=Q/(A\varepsilon_0)$
  - Direction of the electric field will be perpendicular to the selected surface i.e. if considering plate of the capacitor as surface.
- As E =0 outside the plates and $E=(Q/(A\varepsilon_0))$ between the plates.
  - There may be some electric field between the plates because of which some current is present between the plates of the capacitor.
  - Electric Flux through the surface=Φ_E= (EA) =$(QA)/ (A\varepsilon_0)$ =(Q/ ε_0)

- **Assuming Q (charge on capacitor i.e. charging or discharging of the capacitor) changes with time current will be get generated.**
  - **Therefore current I_d =(dQ/dt)**
    - **Where I_d =displacement current**
  - **=>DifferentiatingΦ_E =(Q/ ε_0) on both sides w.r.t time,**
  - **($d\Phi_E$/dt) =(1/ ε_0) (dQ/dt)**
    - **where (dQ/dt) =current**
  - **Therefore (dQ/dt) = ε_0 (d Φ_E/dt)**
  - **=>Current was generated because of change of electric flux with time.**
  - **Electric flux arose because of presence of electric field in the plates of the capacitor.**
  - **I_d = (dQ/dt) = Displacement current**
  - **Therefore Change in electric field gave rise to Displacement current.**
    - **Current won't be 0 it will be I_d.**
    - **There is some current between the plates of the capacitor and there is some current at the surface.**
    - **At certain points there is no displacement current there is only conduction current and vice-versa.**
  - **Maxwell corrected the Ampere's circuital law by including displacement current.**
  - **He said that there is not only the current existed outside the capacitor but also current known as displacement currentexisted between the plates of the capacitor.**
  - **Displacement current exists due to the change in the electric field between the plates of the capacitor.**
  - **Conclusion:-Magnetic fields are produced both by conduction currents and by time varying fields.**

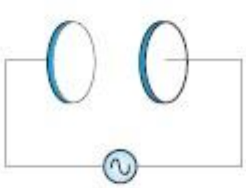


<u>Problem:-</u> A parallel plate capacitor (Fig) made of circular plates each of radiusR = 6.0 cm has a capacitance C = 100 pF. The capacitor is connected toa 230 V ac supply with a (angular) frequency of 300 rad s^{-1}.

(a) What is the rms value of the conduction current?

(b) Is the conduction current equal to the displacement current?

(c) Determine the amplitude of B at a point 3.0 cm from the axisbetween the plates.



Answer:- **Radius of each circular plate, R = 6.0 cm = 0.06 m**
Capacitance of a parallel plate capacitor, C = 100 pF = 100 × 10^{-12} F
Supply voltage, V = 230 V
Angular frequency, ω = 300 rad s^{-1}
(a) Rms value of conduction current, I
Where,
X_C = Capacitive reactance
=1/ (ωC)
Therefore, I = V × ωC
= 230 × 300 × 100 × 10^{-12}
= 6.9 × 10^{-6} A
= 6.9 μA
Hence, the rms value of conduction current is 6.9 μA.
(b) Yes, conduction current is equal to displacement current.
(c) Magnetic field is given as:
B = (μ_0r)/ (2 R^2) I_0 Where,
μ_0 = Free space permeability = 4x πx10^{-7}NA^{-2}
I_0 = Maximum value of current =√2 I
r = Distance between the plates from the axis = 3.0 cm = 0.03 m
Therefore B = (4xπ x10^{-7}x0.03x√2x6.9x10^{-6})/ $(2x\pi\ x0.06)^2$
= 1.63 × 10^{-11} T
Hence, the magnetic field at that point is 1.63 × 10^{-11} T.

Ampere-Maxwell Law

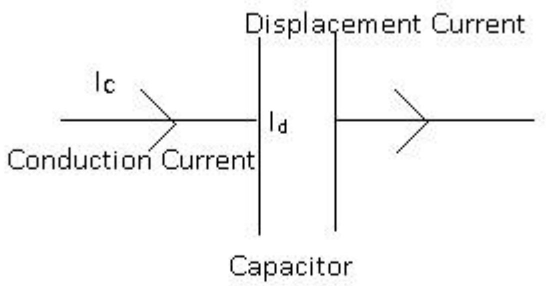
- **As Maxwell was able to correct the shortcomings of the Ampere's circuital law therefore the law came to known as Ampere-Maxwell law.**
- **Current which is arising due to the flow of charges is known as <u>conduction current</u>.**
  - **It is denoted by I_C.**
- **Current which is arising due to change in electric field is known as <u>displacement current</u>.**
  - **It is denoted by I_d.**
- **Therefore I = I_c + I_d where I = total current**
- **Ampere-Maxwell Law stated that**
  - **∫dl = μ_0 (I_c + I_d)**
  - **∫dl = μ_0 I_c + μ_0 ε_0 (d ϕ_E/dt)**
  - **The above expression is known as Modified Maxwell Law**

Displacement Current

- **Consider a capacitor and outside the plates of the capacitor there is conduction current I_C.**
- **Area between the plates i.e. inside the capacitor there is displacement current I_d.**
- **Physical behaviour of displacement current is same as that of induction current.**
- **Difference between Conduction current and Displacement current:-**

Conduction Current	**Displacement Current**
It arises due to the fixed charges.	**It arises due to the change in electric field.**

- **For Static electric fields:-**
  - **I_d=0.**
- **For time varying electric fields:-**
  - **$I_d \neq 0$.**
- **There can be some scenarios where there will be only conduction current and in some case there will be only displacement current.**
  - **Outside the capacitor there is only conduction current and no displacement current.**
  - **Inside the capacitor there is only displacement current and no conduction current.**
- **But there can be some scenario where both conduction as well as displacement current is present i.e. $I = I_C + I_d$.**
- **Applying modified Ampere-Maxwell law to calculate magnetic field at the same point of the capacitor considering different amperial loop,the result will be same.**



Ampere – Maxwell law: Consequences

Case 1 : Magnetic field is given as

- **$\int dl = \mu_0 I_c$**
- **$\int dl = \mu_0 I_c / 2\pi r$**

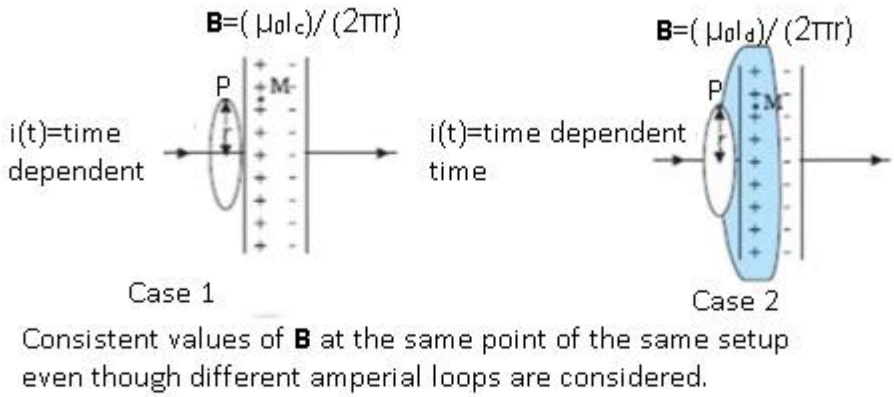
Case 2 : Magnetic field is given as

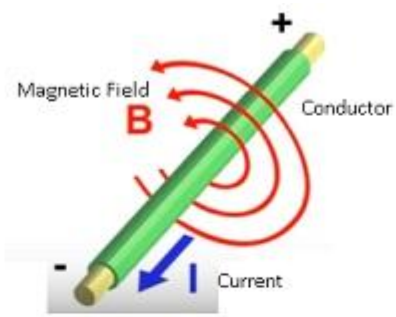
- **$\int dl = \mu_0 I_d$**
- **$\int dl = \mu_0 I_d / 2\pi r$**

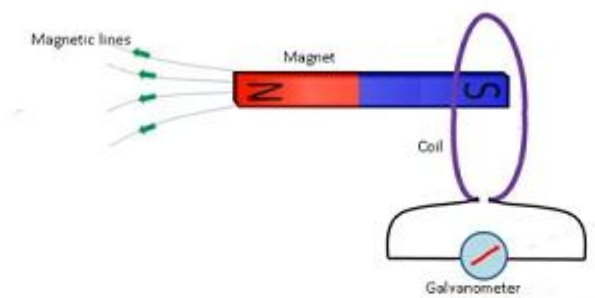
Conclusion: -

1. **The value of B is same in both cases.**
2. **Total current should be the same.**

- **Time varying electric field generatesmagnetic field given by (Ampere-Maxwell law)**
  - **Consider 1st step up there is electric field between the plates and this electric field is varying with time.**
  - **As a result there is displacement current and this displacement current gives rise to magnetic field.**
- **Time varying magnetic field generates electric field given by (Faraday-Lenz law)**
- **Therefore if there is electric field changing with time it generates magnetic field and if there is magnetic field changing with time it generates electric field.**
- **Electromagnetic waves are based on the above conclusion.**



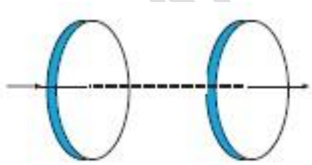




Problem:- **Figure shows a capacitor made of two circular plates each ofradius 12 cm, and separated by 5.0 cm. The capacitor is beingcharged by an external source (not shown in the figure). Thecharging current is constant and equal to 0.15A.(a) Calculate the capacitance and the rate of charge of potentialdifference between the plates.**

(b) Obtain the displacement current across the plates.

(c) Is Kirchhoff's first rule (junction rule) valid at each plate of thecapacitor? Explain



Answer:-

Radius of each circular plate, r = 12 cm = 0.12 m

Distance between the plates, d = 5 cm = 0.05 m

Charging current, I = 0.15 A

Permittivity of free spaceε_0, = 8.85 × 10^{-12} C^2 N^{-1} m^{-2}

(a) Capacitance between the two plates is given by the relation,
$C = (\varepsilon_0 A)/ (d)$
Where,
A = Area of each plate=πr^2
$C= (\varepsilon_0 \pi r^2)/ (d)$
$= (8.85x10^{-12}\pi x0.12x0.12)/ (0.05)$
$=8.0032x10^{-12}F$
=80.032pF
Charge on each plate, q = CV
Where,
V = Potential difference across the plates
Differentiation on both sides with respect to time (t) gives:
(dq/dt)=C (dV/dt)
Bur (dq/dt) =current (I)
Therefore (dV/dt) = (I/C)
$=> (0.15)/ (80.032x10^{-12}) =1.87 \times 10^9$ V/s
Therefore, the change in potential difference between the plates is 1.87×10^9 V/s.
(b) The displacement current across the plates is the same as the conduction current. Hence, the displacement current, id is 0.15 A.
(c) Yes
Kirchhoff's first rule is valid at each plate of the capacitor provided that we take the sum of conduction and displacement for current.

Maxwell's Equations

- **Maxwell's equations describe how an electric field can generate a magnetic field and vice-versa. These equations describe the relationship and behaviour of electric and magnetic fields.**
- **Maxwell gave a set of 4 equations which are known as Maxwell's equations.**
- **According to Maxwell equations:-**
    - **A flow of electric current will generate magnetic field and if the current varies with time magnetic field will also give rise to an electric filed.**
        - **First equation (1) describes the surface integral of electric field.**
        - **Second equation (2) describes the surface integral of magnetic field.**
        - **Third equation (3) describes the line integral of electric field.**
        - **Fourth equation (4) describes line integral of magnetic field.**

First equation (1) describes about the surface integral of electric field.

1 $\oint \vec{E} \cdot d\vec{A} = \frac{Q}{\varepsilon_0}$ Gauss Law in Electrostatics

Second equation (2) describes about the surface integral of magnetic field.

2 $\oint \vec{B} \cdot d\vec{A} = 0$ Gauss law in Magnetism

3 $\oint \vec{E} \cdot d\vec{s} = -\frac{d\Phi_B}{dt}$ Faraday Lenz law Third equation (3) describes about the line integral of electric field.

4 $\oint \vec{B} \cdot d\vec{s} = \mu_0 I + \varepsilon_0 \mu_0 \frac{d\Phi_E}{dt}$ Ampere-Maxwell law Fourth equation (4) describes about line integral of magnetic field.

Q= Charge

$\vec{E}$=Electric field

$\vec{B}$=Magnetic field

$d\vec{A}$ =small area

$\frac{d\Phi_B}{dt}$ = Magnetic Flux

$\oint \vec{E} \cdot d\vec{s}$ =Induced Emf

μ_0 =permeability

ε_0 =permittivity

- **Maxwell was the first to determine the speed of propagation of EM waves is same as the speed of light.**
- **Experimentally it was found that:-**
  - **$c = 1/(\sqrt{\mu_0 \varepsilon_0})$**
- **Where μ_0(permeability) and ε_0(permittivity) and c= velocity of light.**
- **Maxwell's equations show that the electricity, magnetism and ray optics are all inter-related to each other.**

Problem:- **A parallel plate capacitor with circular plates of radius1 m has a capacitance of 1 nF. At t = 0, it is connected for charging inseries with a resistor R = 1 MΩ across a 2V battery (Fig.). Calculatethe magnetic field at a point P, halfway between the centre and theperiphery of the plates, after $t = 10^{-3}$ s. (The charge on the capacitorat time t is q (t) = CV [1 – exp (–t/τ)], where the time constant τ isequal to CR.)**

Answer:- **The time constant of the CR circuit is $\tau = CR = 10^{-3}$ s. Then,we have**

= q (t) = CV [1 – exp (–t/τ)]

$= 2 \times 10^{-9} [1 - \exp(-t/10^{-3})]$

The electric field in between the plates at time t is

$E = q(t)/(\varepsilon_0 A)$

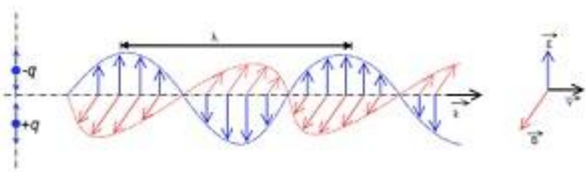
$= q/(\pi\varepsilon_0)$; $A = \pi (1)^2 m^2$ = area of the plates.

Consider now a circular loop of radius (1/2) m parallel to the platespassing through P. The magnetic field B at all points on the loop isalong the loop and of the same value.

The flux Φ_E through this loop is

Φ_E = E × area of the loop
$=E x \pi \times (1/2)^2$
$= (\pi E/4)$
$= (q/4\varepsilon_0)$
The displacement current
$I_d = \varepsilon_0 (d\Phi_E/dt)$
$= (1/4)(dq/dt)$
$=0.5 \times 10^{-6} \exp(-1)$
at $t = 10^{-3}$s. Now, applying Ampere-Maxwell law to the loop, we get
$=B \times 2\pi \times (1/2)$
$=\mu_0(I_C+I_d)$
$=\mu_0(0+I_d)$
$=0.5 \times 10^{-6} \mu_0 \exp(-1)$
or $B = 0.74 \times 10^{-13}$ T

Electromagnetic Waves

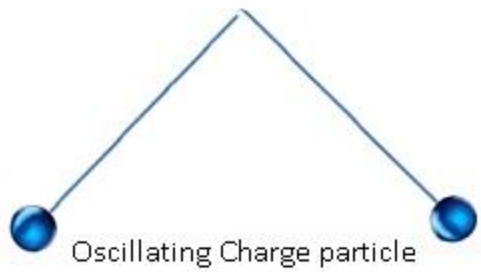


- Electromagnetic waves are coupled time varying electric and magnetic fields that propagate in space.
- Electric field is varying with time, and it will give rise to magnetic field, this magnetic field is varying with time and it gives rise to electric field and the process continues so on.
- These electric and magnetic fields are time varying and coupled with each other when propagating together in space gives rise to electromagnetic waves.
- In the fig, blue line represents the electric field and it varies in the form of a sine wave.
- Themagnetic field as shown in the fig. represented by red line.
- The magnetic field will be a sine wave but ina perpendicular direction to the electric field.
- These both give rise to electromagnetic field.
- If the electric field is along x-axis, magnetic field along y-axis, the wavewill then propagate in the z-axis.
- Electric and magnetic field are perpendicular to each other and to the direction of wave propagation.
- Electric and magnetic fields which is time varying and coupled to each other they give rise to electromagnetic waves.

Sources of Electromagnetic Waves (EM)

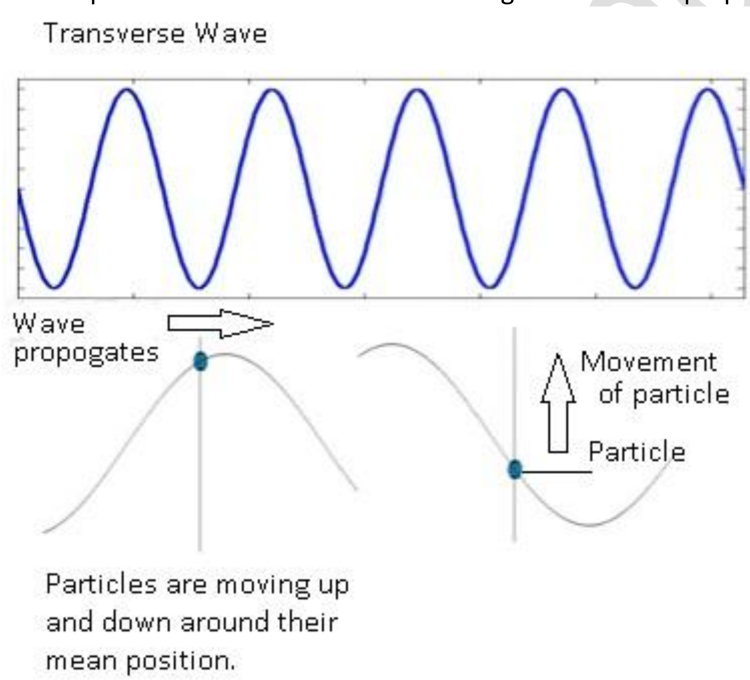
- EM waves are generated by electrically charged particle oscillates (accelerating charges).
- The electric field associated with the accelerating charge vibrates which generates the vibrating magnetic field.
- These both vibrating electric and magnetic fields give rise to EM waves.
- If the charge is at rest,electric field associated with the charge will also be static.
  - There will be no generation of EM waves as electric field is not varying with time.
- When the charge is moving with uniform velocity,thenthe acceleration is 0.
  - The change in electric field with time is also constant as a result again there will be no electromagnetic waves generated.

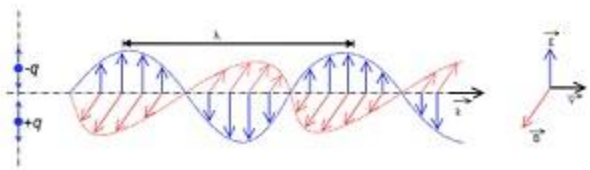
- This shows that only the accelerated charges alone can generate EM waves.
- For example:
    - Consider an oscillating charge particle, it will have oscillating electric field and which give rise to oscillating magnetic field.
    - This oscillating magnetic field in turn give rise to oscillating electric field and so on process continues.
    - The regeneration of electric and magnetic fields are same as propagation of the wave.
    - This wave is known as electromagnetic wave.
    - The frequency of EM waves= the frequency of the oscillating particle.



Nature of EM waves

- EM waves are transverse waves.
- The transverse waves are those in which direction of disturbance or displacement in the medium is perpendicular to that of the propagation of wave.
- The particles of the medium are moving in a direction perpendicular to the direction of propagation of wave.





- In case of EM waves the propagation of wave takes place along x-axis, electric and magnetic fields are perpendicular to the wave propagation.
- This means wave propagation ---à x-axis , electric field ------> y-axis,

magnetic field --à z-axis.

- Because of this EM waves are transverse waves in nature.
- Electric field of EM wave is represented as:
  - **$E_y = E_0 \sin(kx–\omega t)$**
    - Where Ey= electric field along y-axis and x=direction of propagation of wave.
    - Wave number k=(2π/λ)
  - Magnetic field of EM wave is represented as:
    - **$B_z=B_0\sin(kx-\omega t)$**
      - Where B_Z = electric field along z-axis and x=direction of propagation of wave.

Problem:-

Suppose that the electric field amplitude of an electromagnetic wave is E_0 = 120 N/C and thatits frequency is ν = 50.0 MHz (a) Determine, B_0, ω, k, and λ. (b) Find expressions for E andB.

Answer:-

Electric field amplitude, E_0 = 120 N/C

Frequency of source, ν = 50.0 MHz = 50×10^6 Hz

Speed of light, c = 3×10^8 m/s

- Magnitude of magnetic field strength is given as:

$B_0=(E_0/c)$

$=(120)/(3x10^8)=4 x10^{-7}$ T=400nT

Angular frequency of source is given as:

$\omega = 2\pi\nu = 2\pi \times 50 \times 10^6$

$= 3.14 \times 10^8$rad/s

Propagation constant is given as:

k=(ω/c)

$= (3.14 \times 10^8)/ (3x10^8)$ =1.05rad/m

Wavelength of wave is given as:

$\lambda=(c/\nu) =(3x10^8)/(50x10^6) = 6.0$m

(b) Suppose the wave is propagating in the positive x direction. Then, the electric field vectorwill be in the positive y direction and the magnetic field vector will be in the positive zdirection. This is because all three vectors are mutually perpendicular.

Equation of electric field vector is given as:

E=E_0 sin (kx –ωt)ˆj

=120 sin [1.05 x - $3.14x10^8$t]ˆj

And, magnetic field vector is given as:

B=B_0 sin (kx –ωt)ˆk

=4 $x10^{-7}$) sin1.05 x - $3.14x10^8$t]ˆk

-

Problem:-

A plane electromagnetic wave of frequency25 MHz travels in free space along the x-direction. At a particularpoint in space and time, E = 6.3 ˆj V/m. What is B at this point?

Answer:-

Using Eq. $B_0 = (E_0/c)$the magnitude of B is

B= (E/c)

= (6.3 V)/ $(3x10^8 m/s)$

$=2.1 x10^{-8}$ T

To find the direction, we note that E is along y-direction and thewave propagates along x-axis. Therefore, B should be in a directionperpendicular to both x- and y-axes. Using vector algebra, **E × B** shouldbe along x-direction. Since, (+ ˆ**j)** × (+ ˆ**k**) = ˆ**i**, B is along the z-direction.

Thus, $B = 2.1 \times 10^{-8}$ˆ**k**T

Problem:-

The magnetic field in a plane electromagnetic wave isgiven by

$B_y = 2 \times 10^{-7} \sin (0.5\times10^3 x+1.5\times10^{11} t)$ T.(a) What is the wavelength and frequency of the wave?

(b) Write an expression for the electric field.

Answer:-

(a) Comparing the given equation with

$B_y = B_0 \sin [2 \pi ((x/ \lambda) + (t/T))]$

We get, λ = (2 π)/ (0.5x103) m =1.26cm and

$(1/T) = \nu = (1.5 x10^{11})/ (2 \pi)$

= 23.9 GHz

(b) $E_0 = B_0 c = 2\times10^{-7}$ T × 3 × 10^8 m/s = 6 × 10^1 V/m

The electric field component is perpendicular to the direction ofpropagation and the direction of magnetic field. Therefore, theelectric field component along the z-axis is obtained as

$E_z = 60 \sin (0.5 \times 10^3 x + 1.5 \times 10^{11} t)$ V/m

Problem:-

Light with an energy flux of 18 W/cm^2 falls on a non-reflectingsurface at normal incidence. If the surface has an area of20 cm^2, find the average force exerted on the surface during a 30minute time span.

Answer:-

The total energy falling on the surface is

$U = (18 W/cm^2) \times (20 cm^2) \times (30 \times 60)$

$= 6.48 \times 10^5$J

Therefore, the total momentum delivered (for complete absorption) is

$p = (U/c) = (6.48 x 10^5 J)/ (3x10^8 m/s)$

$= 2.16 \times 10^{-3}$ kg m/s

The average force exerted on the surface is

$F = (p/t) = (2.16x10^{-3})/ (0.18x10^4)$

$=1.2 x10^{-6}$ N

How will your result be modified if the surface is a perfect reflector?

Energy of EM wave

- As the EM waves propagate they carry energy.
- Because of this property they have so many practical uses in our day-to-day life.
- Energy in EM wave is partly carried by electric field and partly by magnetic field.
- Mathematically:

- Total energy stored per unit volume in EM wave E_T =Energy stored per unit volume by electric field + Energy stored per unit volume stored in magnetic field.
- $=(1/2)(E^2\varepsilon_0) + (1/2)(B^2\mu_0)$
- Experimentally it has been found that the;
- Speed of the EM wave =Speed of the light c=(E/B)
- => B=(E/c)
- $E_T =(1/2)(E^2\varepsilon_0) + (1/2)(E^2/c^2\mu_0)$
- From Maxwell's equations :- $c=(1/\sqrt{\mu_0\varepsilon_0})$
- Therefore ,$E_T =(1/2)(E^2\varepsilon_0) + (1/2)(E^2\mu_0\varepsilon_0/\mu_0)$
- $=(1/2)(E^2\varepsilon_0) + (1/2)(E^2\varepsilon_0)$
- $\mathbf{E_T = E^2\varepsilon_0}$
- This is the amount of energy carried per unit volume by the EM wave.

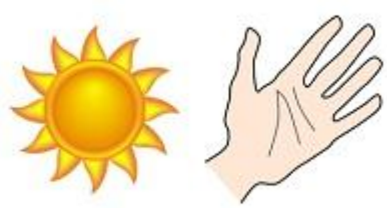
Properties of EM waves

1. Velocity of EM waves in free space or vacuum is a fundamental constant.
- Experimentally it was found that the velocity of EM wave is same as speed of light($c=3\times10^8$m/s).
- The value of c is fundamental constant.
- Therefore , $c=(1/\sqrt{\mu_0\varepsilon_0})$

2. No material medium is necessary for EM waves. But they can propagate with ina medium as well.
- EM waves require time varying electric and magnetic fields to propagate.
- If the medium is present then velocity $v = (1/\sqrt{\mu\varepsilon})$
  - Whereμ =permeability of the medium and ε=permittivity of the medium.
- For example: -Spectacles. When light falls on glass of the spectacle, light rays pass through glass.i.e. Light waves propagate through medium which is glass here.

3. EM waves carry energy and momentum.
- Total energy stored per unit volume in EM wave $\mathbf{E_T= E^2\varepsilon_0}$(partly carried by electric field and partly by magnetic field).
- As EM waves carry energy and momentum, it becomes an important property for its practical purposes.
- EM waves are used for communication purposes, voice communication in mobile phones, telecommunication used in radio.

4. EM waves exert pressure. As they carry energy and momentum, they exert pressure.
- The pressure exerted by EM waves is known as Radiation pressure.
- For example: -
  - The sunlight which we get from sun is in the form of visible light rays.
  - These light rays are also part of EM waves.
  - If we keep our palm in sun,after some time, palm becomes warm and starts sweating.
  - This happens because sunlight is getting transferred in the form of EM waves and these EM waves carry energy.
  - Suppose total energy transferred to the hand =E.
  - Momentum = (E/c) as c is extremely high, therefore momentum is very small.
  - As momentum is very less, pressure experiencedis also very less.
  - This is the reason due to which the pressure exerted by the sun is not experienced by the hand.



Problem:- In a plane electromagnetic wave, the electric field oscillates sinusoidal at a frequency of 2.0×10^{10} Hz and amplitude 48 V m^{-1}.

(a) What is the wavelength of the wave?

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

(c) Show that the average energy density of the E field equals the average energy density of the B field. [$c = 3 \times 10^8$ m s^{-1}.]

Answer:-

Frequency of the electromagnetic wave, $\nu = 2.0 \times 10^{10}$ Hz

Electric field amplitude, $E_0 = 48\ Vm^{-1}$

Speed of light, $c = 3 \times 10^8$ m/s

(a) Wavelength of a wave is given as:

$\lambda=(c/\nu)$

$= (3 \times 10^8)/ (2.0 \times 10^{10})$

$=0.015m$

(b) Magnetic field strength is given as:

$B_0 = (E_0/c)$

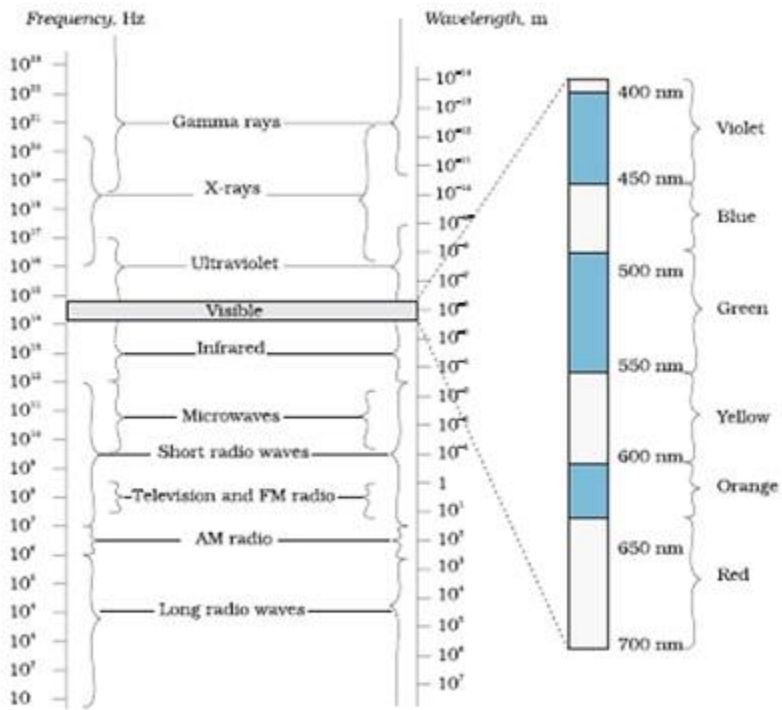
$= (48)/ (3 \times 10^8)$
$=1.6\times10^{-7}$ T
(c) Energy density of the electric field is given as:
$U_E = (1/2) (E^2\varepsilon_0)$
And, energy density of the magnetic field is given as:
$U_B = B^2(1/2\mu_0)$
Where,
ε_0 = Permittivity of free space
μ_0 = Permeability of free space
We have the relation connecting E and B as:
E = cB ... (1)
Where,
$c= (1/\sqrt{\mu_0\varepsilon_0})$ ... (2)
Putting equation (2) in equation (1), we get
$E= (1/\sqrt{\mu_0\varepsilon_0})\ B$
Squaring both sides, we get
$E^2=1/ (\mu_0\varepsilon_0)\ B^2$
$\varepsilon_0 E^2 = (B^2/\mu_0)$
$(1/2)\varepsilon_0 E^2 = (1/2)\mu_0 B^2$
$\Rightarrow U_E=U_B$

Electromagnetic Spectrum

- Electromagnetic spectrum is the classification of EM waves according to their frequency or wavelength.
- Based on the wavelength EM waves are classified into different categories.This classification is known as electromagnetic spectrum.
- Different categories of EM waves in decreasing order of their wavelength:-
  - Radio waves > 0.1m
  - Microwaves 0.1 m - 1mm
  - Infra-Red 1mm – 700 nm
  - Visible light 700nm – 400 nm
  - Ultraviolet 400nm- 1nm
  - X-rays 1nm – 10^{-3}nm
  - Gamma rays <10^{-3}nm
- These 7 waves together constitute the electromagnetic spectrum.

Tip:-

- To remember the order of wavelength of each wave, we can just write the initial letter of all the waves and they are in the order of decreasing wavelength.
- R (max wavelength), M, I, V, U, X and G (minimum wavelength).
- It can be remembered like this Red Man In Violet Uniform X Gun.



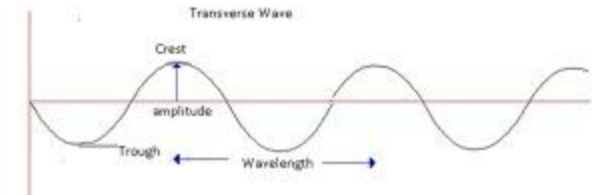
The electromagnetic spectrum, with common names for various part of it. The various regions do not have sharply defined boundaries.

Problem:- A radio can tune in to any station in the 7.5 MHz to 12 MHz band. What is the corresponding wavelength band?

Answer:- A radio can tune to minimum frequency, ν_1 = 7.5 MHz= 7.5 × 10^6 Hz
Maximum frequency, ν_2 = 12 MHz = 12 × 10^6 Hz
Speed of light, c = 3 × 10^8 m/s
Corresponding wavelength for ν_1 can be calculated as:
$\lambda_1 = (c/\nu_1) = (3\times10^8)/(7.5\times10^6) = 40m$
Corresponding wavelength for ν_2 can be calculated as:
$\lambda_2 = (c/\nu_2) = (3\times10^8)/(12\times10^6) = 25m$
Thus, the wavelength band of the radio is 40 m to 25 m.

Electromagnetic energy of each wave in Electromagnetic Spectrum
Electromagnetic waves energy can be described by frequency, wavelength or energy.

1. Frequency- Both micro and radio waves are described in terms of frequencies.
    1. Frequency is number of crests that pass a given point within one second.
    2. Consider a wave which has 3 crests which pass a point in 1 second. Therefore frequency=3Hz.
2. Wavelength-Infrared and visible waves are generally described in terms of wavelength.
    1. Wavelength is the distance between consecutive crests or troughs.
    2. Wavelength can vary from small value to a large value.
    3. I unit: - meter.



3. Energy- X-rays and Gamma rays are described in terms of energies.
    1. An EM wave can be described in terms of energy –in units of eV.
    2. eV is the amount of kinetic energy needed to move 1 electron through a potential of 1 volt.
- Moving along the EM spectrum energy increases as the wavelength decreases.

Relation between Wavelength and Frequency

- c=vλ
    - Whereλ =wavelength and v= frequency.
- =>**λ = (c/v)**
- E=hv
- =(hc/λ)
- => E ∝v and E ∝ (1/λ)
- Therefore from EM spectrum
    - Decreasing order of wavelength->R, M, I, V, U, X and G
    - In terms of increasing order of frequency -> G,X,U,V,I,M,R.

Problem:- The amplitude of the magnetic field part of a harmonic electromagnetic wave in vacuum is B_0 = 510 nT. What is the amplitude of the electric field part of the wave?

Answer:- Amplitude of magnetic field of an electromagnetic wave in a vacuum,
$B_0 = 510\ nT = 510 \times 10^{-9}\ T$
Speed of light in a vacuum, $c = 3 \times 10^8$ m/s
Amplitude of electric field of the electromagnetic wave is given by the relation,
$E = cB_0 = 3 \times 10^8 \times 510 \times 10^{-9} = 153$ N/C
Therefore, the electric field part of the wave is 153 N/C.

Problem:- A plane electromagnetic wave travels in vacuum along z-direction.What can you say about the directions of its electric and magneticfield vectors? If the frequency of the wave is 30 MHz, what is itswavelength?

Answer:- The electromagnetic wave travels in a vacuum along the z-direction. The electric field (E) andthe magnetic field (H) are in the x-y plane. They are mutually perpendicular. Frequency ofthe wave, $v = 30\ MHz = 30 \times 10^6 s^{-1}$
Speed of light in a vacuum, $c = 3 \times 10^8$ m/s Wavelengthof a wave is given as:
$\lambda = (c/v) = (3x10^8)/(30x10^6)$
λ =10m

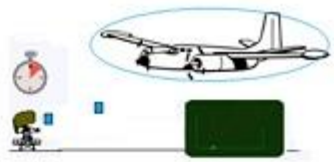
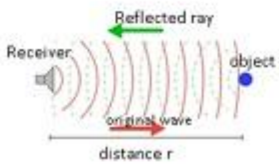
Radio Waves

- Radio waves are produced by the accelerated motion of charges in conducting wires.
- Important application of radio waves is in:-
    - Radio and television communication systems.
    - Mobile phones for voice communication.
- In electromagnetic spectrum the wavelength (λ) of radio waves is >0.1m.
- Radio waves are further classified into different bands:-
    - (Amplitude Modulated)AM band 530 kHz to 1710 kHz (lowest frequency band).They are similar to FM channels.
    - Short wave band – up to 54MHz

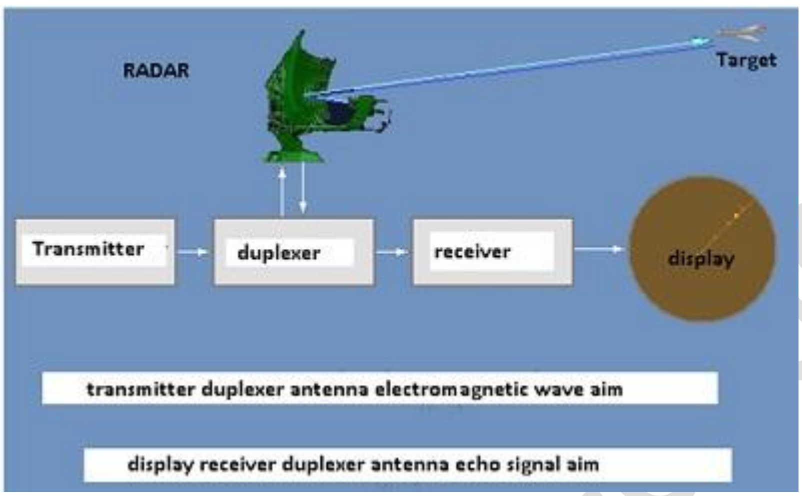
  - TV waves band – 54MHz to 890MHz
  - (Frequency Modulated)FM band – 88MHz to 108MHz
  - UHF band- Ultra high frequency(used for voice communication over cell phones)

Micro Waves

- Micro waves are short wavelength radio waves.
- They are produced by special vacuum tubes (klystrons/magnetrons/Gunn diodes).
- They are used in microwave ovens, and radar system in aircraft navigation.
  - RADAR Technology:-
- RADAR- Radio detection and ranging.
- Different applications of RADAR:-
- Air traffic control:-
  - For example: - To manage air traffic. The pilot should know any other aero plane is present nearby or not.
  - The pilot should know the climatic conditions during take-off and landing.
  - Radar plays very important role in aircraft navigation.
- Speed detection
  - The instruments which are used to detect the speed of the vehicles which move on the roads uses radar technology.
- Military purposes
  - It helps to detect enemies and weapons.
- Satellite tracking
  - In order to track satellites, radar technology is used.





Why Radio waves use micro waves:-

- As they use short wavelength waves which are same as micro waves.
- They are invisible to humans. If we are able to see the waves which get transmitted it will be very irritating.
- Even the smallest presence of microwaves is easy to detect.

Working of Radar Set:-

It consists of:-

1. Transmitter: - It transmits the microwaves.
2. Receiver: - It receives the echo produced by the microwaves when they strike any object. When the receiver receives the reflected ray then it is possible to track the presence of other object in the vicinity.

Microwave ovens

- The following are the properties because of which microwaves are very useful :-
- They have smaller wavelength.
- They get absorbed by water,fats and sugar.

Working of microwave oven:-

- In order to heat anything uniformly microwave ovens are used.
- Any food material will have water, sugar and fats in it.
- When we heat any food material inside the microwave, the microwaves penetrate inside the food.
- So the microwaves get absorbed by the water and the fat molecules.
- The molecules of the food material will start moving randomlywith some frequency.

- This is same as providing some wave to the food material with the same frequency with which the molecules start vibrating.
- This shows that the frequency of microwave matches with the frequency of the molecules.
- As all the molecules are set in random motion, temperature increases and food material gets heated uniformly throughout.
- Object can be heated by 2 ways:-
  - Conduction of heat: - It happens when anything is heated over gas burner.
  - Exciting the molecules: - This technique is used in microwave oven.

Infrared waves

- Infrared waves often known as heat waves as they are produced by hot bodies.
- Their wavelength is lesser than both radio and micro waves.
- They readily get absorbed by water.

Applications:- Infrared lamps/Infrared detector/LED in remote switches of electronic devices/Greenhouse effect.

For example:-

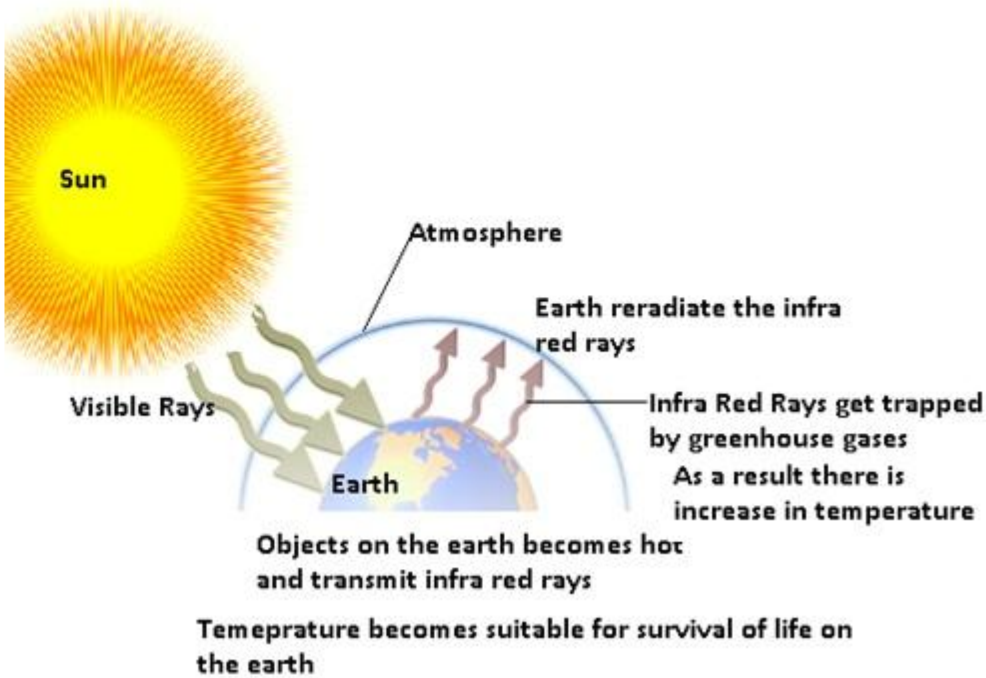
1. Fire gives out both visible light waves and infrared waves.The light rays are visible to us but the infrared wavescannot be seen by us.
2. Humans also generate some infrared waves.

- There are some special glasses which have infrared detector to view infrared waves.
- The infrared lamps are used to heat food materials and sometimes washrooms.
- When we switch on the TV with the help of remote,there is an LED both on TV and on remote.
- The signal gets transferred from remote to TV viainfrared waves.

<u>**Greenhouse Effect:-**</u> Green house effect is an atmospheric heating phenomenon that allows incoming solar radiation to pass through but blocks the heat radiated back from the Earth's surface.

- Consider that the sun gives radiation in the form of visible light to the earth.
- When the visible light reaches the earth's surface all the objects on the earth becomes hot.
- The visible light carries energy from sun and that energy gets transferred to all the objects present on the earth.
- As a result of heat transfer all the objects gets heated up.
- These hot objects transmit infrared waves.
- The earth will reradiate the infrared waves.

- When these infrared waves try to go out of the atmosphere they get trapped by the greenhouse gases (CO_2,CH_4, water vapour).
- As a result heat gets trapped inside the earth which results in an increase in temperature.
- The greenhouse effect makes earth warm because of which the temperature of the earth is suitable for the survival of life on earth.
- Global warming is due toan increase in temperature of the environment, due to pollution.



Visible or Light rays
- Light waves are the most common form of EM wave.
- Their wavelength range is $4x10^{14}$ Hz-$7x10^{14}$
- We are able to see everything because of light rays.
- The radiation which we get from sun is in the form of visible light.

- Most of the insects have compound eyes due to which they see not only the visible light but also the ultraviolet rays.
- Snakes can even see the infrared rays.

Problem:- About 5% of the power of a 100 W light bulb is converted to visibleradiation. What is the average intensity of visible radiation:-

(a) at a distance of 1m from the bulb? at a distance of 10 m?

Answer:- Power rating of bulb, P = 100 W

It is given that about 5% of its power is converted into visible radiation.

Power of visible radiation,
P'=(5/100)x100 =5W.
Hence, the power of visible radiation is 5W.
(a) Distance of a point from the bulb, d = 1 m
Hence, intensity of radiation at that point is given as:
$I=(P'/4x\pi\ xd^2)$
$= (5)/\ (4x\pi x1x1) = 0.398W/m^2$
(b) Distance of a point from the bulb, $d_1 = 10$ m
Hence, intensity of radiation at that point is given as:
$I= (P')/\ (4x\pi\ x(d_1)^2) = 5/(4x\ x100x100)$
$=0.00398W/m^2$

Ultraviolet rays(UV rays)
It covers wavelengths ranging from about 4×10^{-7} m (400 nm) down to 6×10^{-10}m (0.6 nm).
- The UVrays are produced by special lamps and very hot bodies (sun).
- UV rays have harmful effects on humans.
- UV lamps are used to kill germs in water purifiers.
- For example:-
  - When UV rays fall on the skin of humans then it leads to the production of a pigment called melamine which causes tanning of the skin.
- In order to protect from UV rays glasses are used,as they get absorbed by the glasses.
- UV rays help in LASER assisted eye surgery.
  - As UV rays have very short wavelength so they can be focussed into narrow beam of light.

- The ozone layerwhich is present outside the atmosphere protects us from the harmful UV rays.
- Ozone has a property of reflecting the harmful UV rays.
  - But due to the use of CFC (chlorofluorocarbon) ozone layer is depleting.
  - So if ozone layer gets depleted humans will get exposed to harmful UV rays coming from the sun.

X-Rays
- X-Rays are produced by bombarding a metal target by high energy electrons.
- It is very important diagnostic tool.
  - X-Rays have lesser wavelengths as compared to all other waves.
  - Because of this X-Rays can easily penetrate inside the skin (low density material). It either gets reflected or absorbed by the high density material (like bone).
  - In any X-Ray, bones look darker and lighter area is skin.
- It is also used for cancer treatment.
  - In cancer there is unwanted growth of the cells.
  - In order to treat cancer the abnormal growth of cells should be stopped.

- The X-Rays have the ability to damage the living tissue.

This is how it helps in the treatment of cancer

Gamma Rays

- Gamma rays are produced in the nuclear reactions and also emitted by radioactive nuclei.
- It is also used in the treatment of the cancer.
- Gamma rays also have very small wavelength.So they help to kill the growth of unwanted living cells which grow when the body is suffering from cancer.