UNIT – 5
ELECTROMAGNETIC WAVES

Introduction

We studied that the electric field produces a magnetic field (magnetic effects of current) and a magnetic field changing with time gives rise to an electric field(electromagnetic induction). James Clerk Maxwell (1831 -1879) argued that not only an electric current but also a time varying electric field generates magnetic field. He formulated a set of equations known as Maxwell's equations involving electric and magnetic fields. The most important prediction to emerge from Maxwell's equations is the existence of electromagnetic waves, which are time varying electric and magnetic fields propagating in space. The speed of the waves, according to his equations turned out to be very close to the speed of light obtained from optical instruments. This led to the conclusion that light is an electromagnetic wave. Maxwell's work thus unified the domain of electricity, magnetism and light. Hertz experimentally demonstrated the existence of electromagnetic waves. Its technological use by Marconi , Bose and others led in due course to the revolution in communication that we are witnessing today.

Sources of Electromagnetic Waves

Neither stationary charges nor charges in uniform motion can be sources of electromagnetic waves. The former produces only electrostatic fieldswhile the later also produces magnetic fields which do not vary with time. According to Maxwell's theory accelerated charges radiate electromagnetic waves.

Consider a charge oscillating with some frequency. 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 and as a result the wave propagates through the space. The frequency of the electromagnetic wave naturally equals the frequency of oscillation of the charge.

From the above discussion it might appear easy to test the prediction that light is an electromagnetic wave. But at present it is not possible, because for the production of say yellow light having frequency $6\times10^{14}\,Hz$ we have to set up an oscillator circuit having frequency $6\times10^{14}\,Hz$. But even with the modern electronic circuit the frequency generated is hardly above $10^{11}\,Hz$. This is why the experimental demonstration of electromagnetic wave had to come in the low frequency region.

The experiment that conclusively demonstrated the existence of electromagnetic waves was first performed by Heinrich Hertz in 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 culcutta, succeeded in producing and observing electromagnetic waves of much shorter wavelength (25mm to 5mm). At around the same time 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.

Hertz's Demonstration of Electromagnetic Waves

The experiment that conclusively demonstrated the existence of electromagnetic waves was first performed by Heinrich Hertz in 1887. The experimental arrangement is as shown in the figure.

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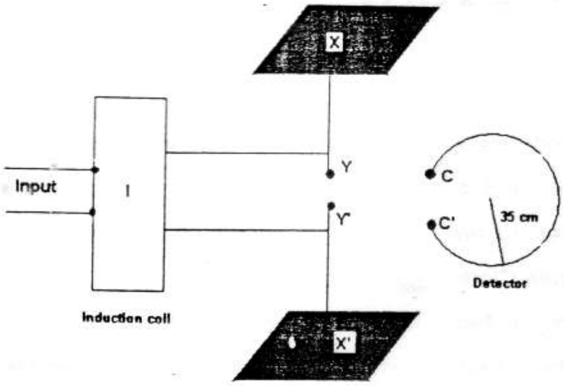
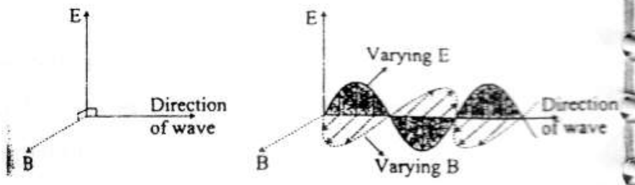


Two large metal spheres Y and Y' are attached to two large metal plates X and X' respectively. The spheres are connected to an induction coil Interrupting currents in an induction coils, a sudden high voltage is applied across the gap. The voltage is high enough to ionize the air in the gap and sparks jumps the gap. Since the air is ionized, the spark gap consists of electrons and ions from the air which oscillate back and forth. This process results in the production of electromagnetic waves. The frequency of electromagnetic waves s determined by the inductance and capacitance of the coils or rods that form the gap.

To detect these waves, Hertz designed a detector which consisted of a single loop of wire connected to two spheres C and C'. It had its own effective inductance, capacitance and natural frequency of oscillation. The electromagnetic waves reaching the gap of the detector had an electric field strong enough to establish a high potential difference between the gap CC' and cause a spark. This shows the presence of electromagnetic radiations. The production of sparks is maximum when CC' is parallel to YY' and there is no spark when the gaps are perpendicular to each other. This shows that the electric vector of radiation produced by the source gap is parallel to the two gaps, ie in a direction perpendicular to the direction of propagation of the wave. This clearly demonstrates that the electromagnetic waves are transverse waves.

Nature of Electromagnetic Waves



The diagram shows the electric and magnetic fields in the case of an electromagnetic wave. Here electromagnetic wave is propagating along X axis, electric and magnetic fields are along Y-axis and Z-axis respectively.

The electric field,

$$E = E_y \hat{j} = E_0 \sin\left[kx - \omega t\right] j$$

Where $k = \dfrac{2\pi}{\lambda}$ and $\omega = 2\pi\nu$.

$$c = \frac{\omega}{k} = \frac{2\pi\nu}{2\pi/\lambda} = \nu\lambda = c$$

$$\therefore E = E_0 \sin\left\{2\pi\left[\frac{x}{\lambda} - \nu t\right]\right\}\hat{j}$$

$$= E_0 \sin\left\{2\pi\left[\frac{x}{\lambda} - \frac{t}{T}\right]\right\}\hat{j}$$

Where λ is the wavelength and $\nu = \dfrac{1}{T}$ is the frequency, and T is the time period.

There is no electric field along X axis and Z axis.

$$\therefore E_x = E_z = 0$$

The magnetic field ,

$$B = B_y \hat{k} = B_0 \sin\left[kx - \omega t\right] k$$

Where $k = \dfrac{2\pi}{\lambda}$ and $\omega = 2\pi\nu$.

$$\therefore B = B_0 \sin\left\{2\pi\left[\frac{x}{\lambda} - \nu t\right]\right\} k$$

$$= B_0 \sin\left\{2\pi\left[\frac{x}{\lambda} - \frac{t}{T}\right]\right\}\hat{k}.$$

Where λ is the wavelength and $\nu = \dfrac{1}{T}$ is the frequency and T is the time period

There is no electric field along X axis and Y axis.

$\therefore B_x = B_y = 0$

In the above equations E_0 and B_0 are the amplitudes of electric field and magnetic field respectively. The magnitudes of E and B are related by $\frac{E}{B} = c$ or $\frac{E_0}{B_0} = c$ where c is the speed of electromagnetic waves. Maxwell showed that the speed of electromagnetic waves is related to the permeability and the permittivity of the medium through which it propagates. The speed of an electromagnetic wave in free space is given by

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

Where $\mu_0 = 4\pi \times 10^{-7} Ns^2/C^2$ is the permeability of free space and $\varepsilon_0 = 8.85 \times 10^{-12} C^2/Nm^2$.

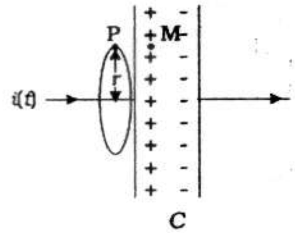
$$c = 2.99792 \times 10^8 m/s$$

In any other medium the velocity of electromagnetic wave $v = \frac{1}{\sqrt{\mu\varepsilon}} = \frac{1}{\sqrt{\mu_0 \mu_r \varepsilon_0 \varepsilon_r}} = \frac{c}{\sqrt{\mu_r \varepsilon_r}}$.

Displacement current

We have seen that an electrical current produces a magnetic field around it. Maxwell showed that for logical consistency, a changing electric field must also produce a magnetic field. This effect is of great importance because it explains the existence of radio waves, gamma rays and visible light, as well as all other forms of electromagnetic waves.

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 given by $\int B.dl = \mu_0 i(t)$ to find magnetic field at a point outside the capacitor.

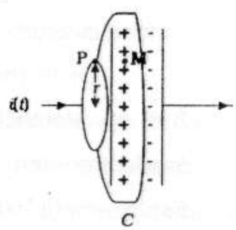


(a)

Figure shows a parallel plate capacitor C which is a part of circuit through which a time-dependent current i(t) flows to charge the capacitor . Let us find the magnetic field at a point such as P, in a region outside the parallel plate capacitor. For this, we consider a plane circular loop of

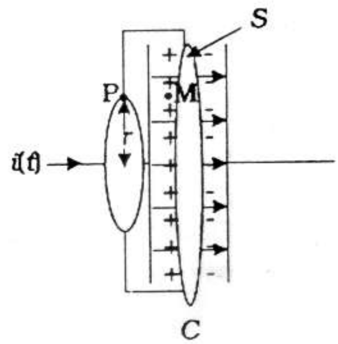
radius r whose plane is perpendicular to the directionof the current-carrying wire, and which is centred symmetrically with respect to the wire . From symmetry, the magnetic field is directed along the circumference of the circular loop and is the same in magnitude at all points on the loop so that if B is the magnitude of the field, then we have $B \times 2\pi r = \mu_0 i(t)$.

Now, consider a different surface, which has the same boundary. This is a pot like surface



(b)

which nowhere touches the current, but has its bottom between the capacitor plates; its mouth is the circular loop mentioned above. Another such surface is shaped like a tiffin box (without the lid)



(c)

On applying Ampere's circuital law to such surfaces with the same perimeter, we find that the left hand side of the above equation has not changed but the right hand side is zero and not $\mu_0 i$. since no current passes through the surface of (b) and (c). 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. Since the contradiction arises from our use of Ampere's circuital law, this law must be missing something. The missing term must be such that one gets the same magnetic field at point P, no matter what surface is used.

Or in the simplest sense Maxwell assumed that all electric currents must be closed. In the condenser the conduction current is closed by displacement current in the dielectric between the plates. ie inside the capacitor through the surface S between the plates of the capacitor there is electric field. If the plates of the capacitor have an area A, and a total charge Q, the magnitude of the electric field **E** between the plates is $E=\frac{\sigma}{\varepsilon_0}=\frac{Q}{A\varepsilon_0}$. The field is perpendicular to the surface S of figure c. It has the same magnitude over the area A of the capacitor plates, and vanishes outside it. So the electric flux ϕ_E through the surface S is (using Gauss's law),

$$\phi_E=|E|A=\frac{\sigma}{\varepsilon_0}A=\frac{Q}{A\varepsilon_0}A=\frac{Q}{\varepsilon_0}\;.....(1)$$

Now if the charge Q on the capacitor plates change with time, there is a current $i=\frac{dQ}{dt}$

Differentiating (1) w.r.t time

$$\frac{d\phi_E}{dt}=\frac{d\left(Q/\varepsilon_0\right)}{dt}=\frac{1}{\varepsilon_0}\frac{dQ}{dt}$$

$$\frac{d\phi_E}{dt}=\frac{1}{\varepsilon_0}i \quad \therefore i=\varepsilon_0\frac{d\phi_E}{dt}$$

This is the missing term in Ampere's circuital law. we generalize this law by adding to the total curre[nt] carried by conductors through the surface, anoth[er] term which is ε_0 times the rate of change [of] electricflux through the same surface, the total ha[s] the same value of current I for all surfaces. If this [is] done, there is no contradiction in the value of [B] obtained anywhere using the generalised Ampere['s] law. B at the point P is non-zero no matter whic[h] surface is used for calculating it. B at a point outside the plates (fig a) is the same as at a point just inside, as it should be. The current carried b[y] conductors due to flow of charges is calle[d] conduction current. The current, given [by] $i=\varepsilon_0\frac{d\phi_E}{dt}$ is a new term, and is due to chang[ing] electric field (or electric displacement, an old te[rm] still used sometimes). It is, therefore, cal[led] displacement current or Maxwell's displaceme[nt] current.

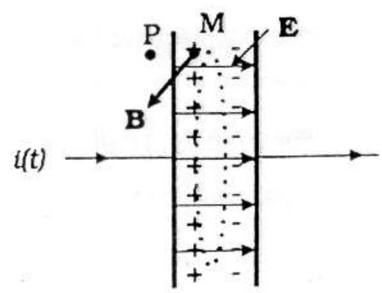


Figure above shows the electric and magnetic fie[lds] inside the parallel plate capacitor discussed abov[e]. The generalisation made by Maxwell then is [the] following. The source of a magnetic field is not j[ust] the conduction electric current due to flowing charges, but also the time rate of change 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 $i_d = \varepsilon_0 \frac{d\phi_E}{dt}$. So we have $i = i_c + i_d = i_c + \varepsilon_0 \frac{d\phi_E}{dt}$ In explicit terms, 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 $i_d = i$.

The generalised (and correct) Ampere's circuital law has the same form as $\int B.dl = \mu_0 i(t)$ with one difference: "the total current passing through any surface of which the closed loop is the perimeter" is the sum of the conduction current and the displacement current.

The generalised law is $\int B.dl = \mu_0 i_c + \mu_0 \varepsilon_0 \frac{d\phi_E}{dt}$ and is known as Ampere-Maxwell law. In all respects, the displacement current has the same physical effects as the conduction current. In some cases, for example, steady electric fields in a conducting wire, the displacement current may be zero since the electric field **E** does not change with time. In other cases, for example, the charging capacitor above, both conduction and displacement currents may be present in different regions of space. In most of the cases, they both may be present in the same region of space, as there exist no perfectly conducting or perfectly insulating medium. Most interestingly, there may be large regions of space where there is no conduction current, but there is only a displacement current due to time-varying electric fields. In such a region, we expect a magnetic field, though there is no (conduction) current source nearby! The prediction of such a displacement current can be verified experimentally. For example, a magnetic field (say at point M) between the plates of the capacitor in Fig. 8.2(a) can be measured and is seen to be the same as that just outside (at P). The displacement current has (literally) far reaching consequences. One thing we immediately notice is that the laws of electricity and magnetism are now more symmetrical. Faraday's law of induction states that there is an induced emf equal to the rate of change of magnetic flux. Now, since the emf between two points 1 and 2 is the work done per unit charge in taking it from 1 to 2, the existence of an emf implies the existence of an electric field. So, we can rephrase Faraday's law of electromagnetic induction by saying that a magnetic field, changing with time, gives rise to an electric field. Then, the fact that an electric field changing with time gives rise to a magnetic field, is the symmetrical counterpart, and is a consequence of the displacement current being a source of a magnetic field. Thus, time- dependent electric and magnetic fields give rise to each other! Faraday's law of electromagnetic induction and Ampere-Maxwell law give a quantitative expression of this statement, with the current being the total current.

Characteristics of Displacement Current

- Displacement current is a current only in the sense that it produces a magnetic field
- The magnitude of the displacement current is equal to the rate of change of electric displacement vector
- The displacement current serves the purpose to make the total current continuous across the discontinuity in a conduction current.

Maxwell's Equations	
$\int E.dA = \frac{Q}{\varepsilon_0}$	Gauss's law for electricity
$\int B.dA = 0$	Gauss's law for magnetism

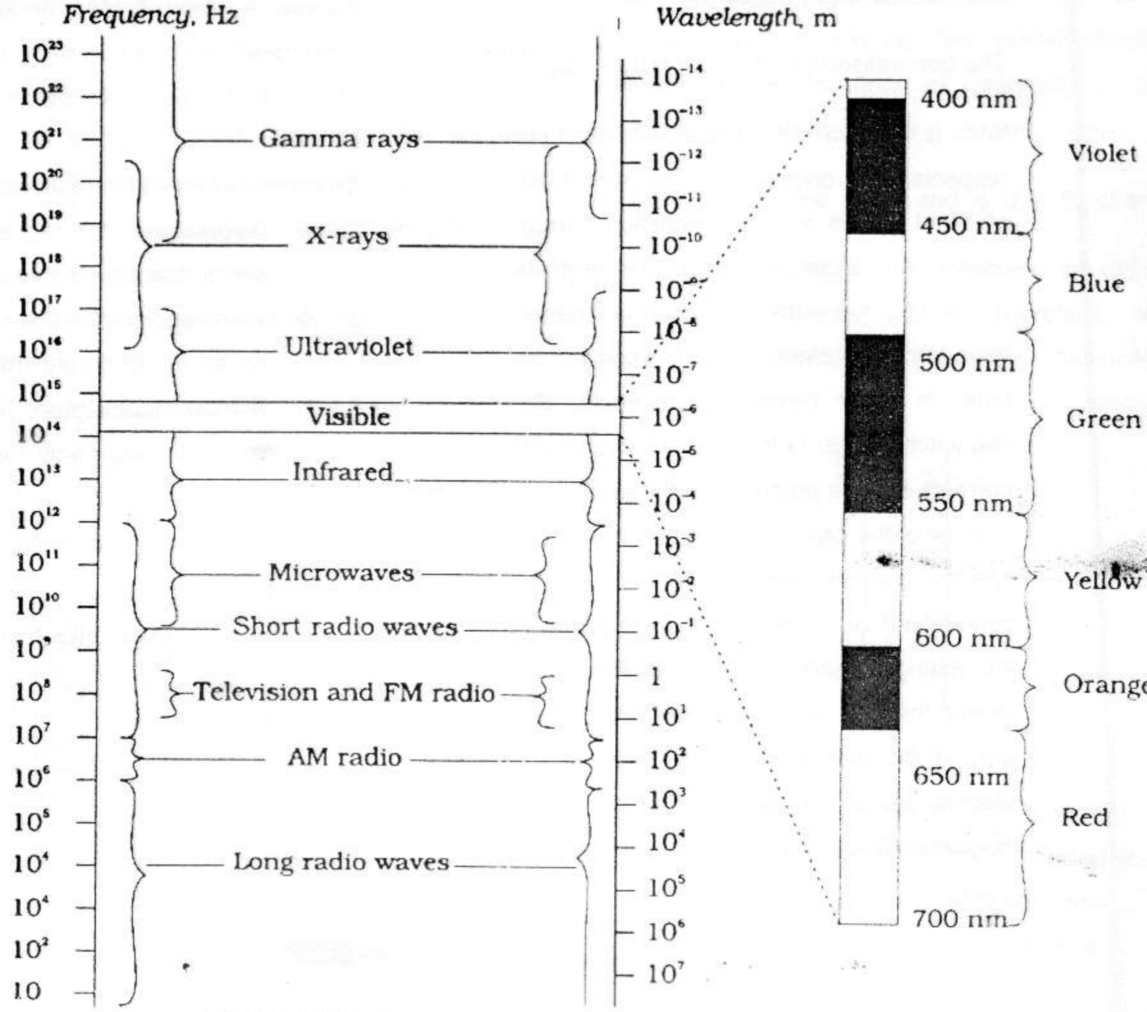
$\int E.dl = -\frac{d\phi_B}{dt}$	Faraday's law
$\int B.dl = \mu_0 i_c + \mu_0 \varepsilon_0 \frac{d\phi_E}{dt}$	Ampere-Maxwell law

Electromagnetic Spectrum

The classification of electromagnetic waves according to frequency is the electromagnetic spectrum. The electromagnetic spectrum consists of gamma rays , X-rays, ultra violet rays, visible light, infra red radiation, microwaves, radio waves etc. A small part of the electromagnetic spectrum ie visible spectrum is the only part of the spectrum visible to human beings. Since our eye cannot see the spectrum beyond the red and violet extremes, this part of the spectrum is called the invisible spectrum. The portion of the spectrum just beyond the red end is called the infrared spectrum while the portion of the spectrum beyond the violet end is called ultraviolet spectrum.

Common Properties of Electromagneti[c] Radiations

* All the electromagnetic waves travel with t[he] same speed which is equal to the speed of lig[ht] $3\times10^8 m/s$ in vacuum $c = \frac{1}{\sqrt{\mu_0\varepsilon_0}}$.
* These waves do not require a medium [for] propagation.
* Electric and magnetic fields in a[n] electromagnetic wave in free space are alwa[ys] perpendicular to each other and al[so] perpendicular to the direction of propagation [of] the wave.
* The electric and magnetic fields have the sa[me] frequency and are in phase.



* Electromagnetic waves carry energy and momentum.
* When electromagnetic wave strikes a surface it exerts a pressure on the surface. If the total energy transferred to the surface in time t is U, the total momentum delivered to the surface is $P=\frac{U}{c}$
* They exhibit properties of reflection and refraction
* They show phenomena of interference and diffraction
* They show the phenomenon of polarisation. Thus electromagnetic waves are transverse in nature.

Simple Properties and Uses of Different Electromagnetic Radiations

☼ **Radio waves :** Radio waves are produced by the accelerated motion of charges in conducting wires. These are the waves with very high wavelength . The frequency of radio wave is below $10^7 Hz$ .It may extent up to $10^9 Hz$. The wavelength is around $10^{11}\overset{o}{A}$ These waves are used mainly in communication as waves of short and medium band in the radio receiver and for TV communication systems. The cellular phone also uses radio waves(UHF).

They are used in radio and television communication systems. They are generally in the frequency range from 500 kHz to about 1000 MHz. The AM (amplitude modulated) band is from 530 kHz to 1710 kHz. Higher frequencies upto 54 MHz are used for *short wave* bands. TV waves range from 54 MHz to 890 MHz. The FM (frequency modulated) radio band extends from 88 MHz to 108 MHz. Cellular phones use radio waves to transmit voice communication in the ultrahigh frequency (UHF) band.

☼ **Micro waves :** Microwaves(short wavelength radio waves), with frequencies with in the gigahertz range are produced by special vacuum tubes(called klystrons, magnetrons and gunn diodes). The frequency range $10^7-10^{11} Hz$. The wavelength range from $3\times10^7\overset{o}{A}-10^{11}\overset{o}{A}$. They are used in communication for transmission of RADAR and TV signals. Micro waves are often used to transmit telephone conversation. Micro wave ovens are used for cooking.

☼ **Infrared Rays :** The frequency range $10^{11}-8\times10^{14} Hz$. The infrared region extends from The wavelength range from $8000\overset{o}{A}-3\times10^7\overset{o}{A}$.The are invisible radiations which produce a heating effect. This is because water molecules present in most of the materials readily absorb infrared rays and after absorption their thermal motion increases , that is, they heat up and heat the surroundings. Many other molecules like carbondioxide, ammonia etc also absorb infrared rays. They do not affect ordinary photographic plates, however they affect specially treated photographic film. They are detected by heating property using a thermopile or blackened bulb thermometer. They are used for therapeutic purposes by doctors, in photography and as signal lights, since they are scattered less by the atmospheric air because of their long wavelength. Infrared radiation also plays an important role in maintaining the earth's warmth or average temperature through the green house effect.

Visible Spectrum

Colour	Frequency range $10^{14} Hz$	Wavelength range nearly($\overset{o}{A}$)
Violet	6.73-7.6	3800-4460
Indigo	6.47-6.73	4460-4640

Blue	6.01-6.47	4640-5000
Green	5.19-6.01	5000-5780
Yellow	5.07-5.19	5780-5920
Orange	4.84-5.07	5920-6200
Red	3.75-4.84	6200-7800

- **Ultraviolet Rays** : The frequency range $4\times10^{14}-10^{16}Hz$. The ultraviolet radiations extend in the range of wavelength The wavelength range from $100\overset{o}{A}-4000\overset{o}{A}$. The sun is an important source of ultra violet light. They can pass through quartz but ordinary glass absorbs ultraviolet radiations. They strongly affect the photographic plate as they are most chemically active. They provide vitamin-D to our body. They are used for sterilizing purposes, to detect the purity of gems, eggs, ghee etc
  Welders wear special glass goggles or face masks with glass windows to protect their eyes from large amount of UV produced by welding arcs. Due to its shorter wavelengths, UV radiations can be focussed into very narrow beams for high precision applications such as LASIK (Laserassisted in situ keratomileusis) eye surgery. UV lamps are used to kill germs in water purifiers.
- **X-Rays** : The frequency range $10^{16}-10^{19}Hz$. The wavelength range The wavelength range from $0.1\overset{o}{A}-100\overset{o}{A}$.They are used for detecting fracture in bones, teeth etc and they are used for studying atomic arrangement in crystals and complex molecules.
- **Gamma Rays** : The frequency range above $10^{19}Hz$. The wavelength is shorter than The wavelength range from $0.1\overset{o}{A}$.They are use in medical science to kill cancer cells and in industry to check welding.

Green house Effect

The atmosphere permits the life giving radiation to pass through it, but provides a protecting cover from the harmful radiation such as X-rays, ultraviolet rays etc. These radiations are absorbed by the ozone layer. Energy from the sun heats the earth which itself radiates infrared radiation. However earth being at a lower temperature emits infrared radiation of longer wavelength. These are unable to cross the lower atmosphere as it reflects them back. On this account earth's atmosphere is richer in infra red radiation or thermal radiation. Low lying clouds too prevent escape of infra red radiation thus keeping the earth warm. This phenomenon is called *green house effect*.