13. Electromagnetic Waves and Communication System

Can you recall?

1. What is a wave?
2. What is the difference between longitudinal and transverse waves?
3. What are electric and magnetic fields and what are their sources?
4. What are Lenz's law, Ampere's law and Faraday's law?
5. By which mechanism heat is lost by hot bodies ?

13.1 Introduction :

The information age in which we live is based almost entirely on the physics of electromagnetic (EM) waves. We are now globally connected by TV, cellphone and internet. All these gadgets use EM waves as carriers for transmission of signals. Energy from the Sun, an essential requirement for life on Earth, reaches us by means of EM waves that travel through nearly 150 million km of empty space. There are EM waves from light bulbs, heated engine blocks of automobiles, x-ray machines, lightning flashes, and some radioactive materials. Stars, other objects in our milky way galaxy and other galaxies are known to emit EM waves. Hence, it is important for us to make a careful study of the properties of EM waves.

13.2 EM wave:

There are four basic laws which describe the behaviour of electric and magnetic fields, the relation between them and their generation by charges and currents. These laws are as follows.

(1) Gauss' law for electrostatics, which is essentially the Coulomb's law, describes the relationship between static electric charges and the electric field produced by them.

(2) Gauss' law for magnetism, which is similar to the Gauss' law for electrostatics mentioned above, states that "magnetic monopoles which are thought to be magnetic charges equivalent to the electric charges, do not exist". Magnetic poles always occur in pairs.

(3) Faraday's law which gives the relation between electromotive force (emf) induced in a circuit when the magnetic flux linked with the circuit changes.

(4) Ampere's law gives the relation between the induced magnetic field associated with a loop and the current flowing through the loop. Maxwell (1831-1879) noticed a major flaw in the Ampere's law for time dependant fields. He noticed that the magnetic field can be generated not only by electric current but also by changing electric field. Therefore in the year 1861, he added one more term to the equation describing this law. This term is called the displacement current. This term is extremely important and the EM waves which are an outcome of these equations would not have been possible in absence of this term.

As a result, the set of four equations describing the above four laws is called Maxwell's equations.

In 1888, H. Hertz (1857-1894) succeeded in producing and detecting the existence of EM waves. He also demonstrated their properties namely reflection, refraction and interference.

In 1895, an Indian physicist Sir Jagdish Chandra Bose (1858-1937) produced EM waves ranging in wavelengths from 5 mm to 25 nm. His work, however, remained confined to laboratory only.

In 1896, an Italian physicist G. Marconi (1874-1937) became pioneer in establishing wireless communication. He was awarded the Nobel prize in physics in 1909 for his work in developing wireless telegraphy, telephony and broadcasting.

13.2.1 Sources of EM waves:

According to Maxwell's theory, "accelerated charges radiate EM 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. Thus varying electric and magnetic fields regenerate each other.

Waves that are caused by the acceleration of charged particles and consist of electric and magnetic fields vibrating sinusoidally at right angles to each other and to the direction of propagation are called EM waves or EM radiation. Figure 13.1 shows an EM wave propagating along *z*-axis. The time varying electric field is along the *x*-axis and time varying magnetic field is along the *y*-axis.

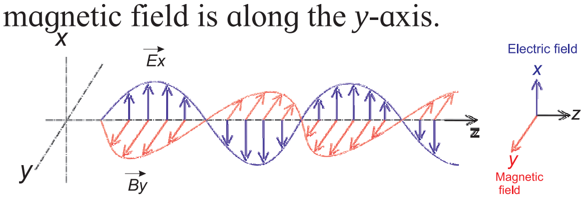

Fig. 13.1: EM wave propagating along *z*-axis.

Do you know ?

In 1865, Maxwell proposed that an oscillating electric charge radiates energy in the form of EM wave. EM waves are periodic changes in electric and magnetic fields, which propagate through space. Thus, energy can be transported in the form of EM waves.

Maxwell's Equations for Charges and Currents in Vacuum

1) $\int \vec{E}\cdot\vec{dS} = \dfrac{Q_{in}}{\varepsilon_0}$ (Gauss' law)

Here $\vec{E}$ is the electric field and ε_0 is the permittivity of vacuum. The integral is over a closed surface *S*. The law states that electric flux through any closed surface *S* is equal to the total electric charge Q_{in} enclosed by the surface divided by ε_0. Gauss' law describes the relation between an electric charge and electric field it produces.

2) $\int \vec{B}\cdot\vec{dS} = 0$ (Gauss' law for magnetism).

Here $\vec{B}$ is the magnetic field. The integral is over a closed surface *S*. The law states that magnetic flux through a closed surface is always zero, i.e., the magnetic field lines are continuous closed curves, having neither beginning nor end.

3) $\int \vec{E}\cdot\vec{dl} = -\dfrac{d\phi_{\mathrm{m}}}{dt}$

(Faraday's law with Lenz's law)

Here ϕ_m is the magnetic flux and the integral is over a closed loop. Time varying magnetic field induces an electromotive force (emf) and hence, an electric field. The direction of the induced emf is such that the change is opposed.

4) $\int \vec{B}\cdot\vec{dl} = \mu_0 I + \varepsilon_0\mu_0\dfrac{d\phi_{\mathrm{E}}}{dt}$

(Ampere-Maxwell law)

Here μ_0 is the permeability of vacuum and the integral is over a closed loop, *I* is the current flowing through the loop. ϕ_E is the electric flux linked with the circuit. Magnetic field is generated by moving charges and also by varying electric fields.

13.2.2 Characteristics of EM waves:

1) The electric and magnetic fields, $\vec{E}$ and $\vec{B}$ are always perpendicular to each other and also to the direction of propagation of the EM wave. Thus the EM waves are transverse waves.
2) The cross product $\vec{E}\times\vec{B}$ gives the direction in which the EM wave travels. $\vec{E}\times\vec{B}$ also gives the energy carried by EM wave.
3) The $\vec{E}$ and $\vec{B}$ fields vary sinusoidally and are in phase.
4) EM waves are produced by accelerated electric charges.
5) EM waves can travel through free space as well as through solids, liquids and gases.
6) In free space, EM waves travel with velocity *c*, equal to that of light in free space.

$$c = \frac{1}{\sqrt{\mu_0\varepsilon_0}} = 3\times10^8\,\mathrm{m/s},$$

where μ_0 ($4\pi\times10^{-7}$ Tm/A) is permeability and ε_0 (8.85×10^{-12} C^2/Nm^2) is permittivity of free space.

7) In a given material medium, the velocity (v_m) of EM waves is given by $v_m = \dfrac{1}{\sqrt{\mu\varepsilon}}$ where μ is the permeability and ε is the

permittivity of the given medium.

8) The EM waves obey the principle of superposition.

9) The ratio of the amplitudes of electric and magnetic fields is constant at any point and is equal to the velocity of the EM wave.

$$|\vec{E_0}| = c\,|\vec{B_0}| \text{ or } \frac{|\vec{E_0}|}{|\vec{B_0}|} = \frac{1}{\sqrt{\mu_0\varepsilon_0}} \quad \text{--- (13.1)}$$

$|\vec{E_0}|$ and $|\vec{B_0}|$ are the amplitudes of $\vec{E}$ and $\vec{B}$ respectively.

10) As the electric field vector ($\vec{E}_0$) is more prominent than the magnetic field vector ($\vec{B}_0$), it is responsible for optical effects due to EM waves. For this reason, electric vector is called light vector.

11) The intensity of a wave is proportional to the square of its amplitude and is given by the equations

$$I_E = \frac{1}{2}\varepsilon_0 E_0^{\,2},\ I_B = \frac{1}{2}\frac{B_0^{\,2}}{\mu_0} \quad \text{--- (13.2)}$$

12) The energy of EM waves is distributed equally between the electric and magnetic fields. $I_E = I_B$

Example 13.1: Calculate the velocity of EM waves in vacuum.

Solution: The velocity of EM wave in free space is given by

$$c = \frac{1}{\sqrt{\mu_0\varepsilon_0}} = \frac{1}{\sqrt{(8.85\times10^{-12}\,\frac{\mathrm{C}^2}{\mathrm{Nm}^2})(4\pi\times10^{-7}\,\frac{\mathrm{T.m}}{\mathrm{A}})}}$$

$$c = 3.00\times10^{+8}\,\mathrm{m/s}$$

Example 13.2: In free space, an EM wave of frequency 28 MHz travels along the *x*-direction. The amplitude of the electric field is E = 9.6 V/m and its direction is along the *y*-axis. What is amplitude and direction of magnetic field B?

Solution : We have,

$$|B| = \frac{|E|}{c} = \frac{9.6\ \mathrm{V/m}}{3\times10^8\,\mathrm{m/s}}$$

$$B = 3.2\times10^{-8}\,\mathrm{T}$$

It is given that E is along *y*-direction and the wave propagates along *x*-axis. The magnetic field B should be in a direction perpendicular to both *x*- and *y*-axes. As per property (2) of EM waves, $\vec{E}\times\vec{B}$ should be along the direction of propagation which is along the *x*- axis

Since $(+\hat{j}) \times (+\hat{k}) = \hat{i}$, B is along the $\hat{k}$, i.e., along the *z*-direction.

Thus, the amplitude of B = 3.2×10^{-8} T and its direction is along the *z*-axis.

Do you know ?

According to quantum theory, an electron, while orbiting around the nucleus in a stable orbit does not emit EM radiation even though it undergoes acceleration. It will emit an EM radiation only when it falls from an orbit of higher energy to one of lower energy.

EM waves (such as X-rays) are produced when fast moving electrons hit a target of high atomic number (such as molybdenum, copper, etc.).

An electric charge at rest has an electric field in the region around it but has no magnetic field. When the charge moves, it produces both electric and magnetic fields. If the charge moves with a constant velocity, the magnetic field will not change with time and as such it cannot produce an EM wave. But if the charge is accelerated, both the magnetic and electric fields change with space and time and an EM wave is produced. Thus an oscillating charge emits an EM wave which has the same frequency as that of the oscillation of the charge.

Example 13.3: A beam of red light has an amplitude 2.5 times the amplitude of second beam of the same colour. Calculate the ratio of the intensities of the two waves.

Solution: Intensity $\propto$ (Amplitude)^2

$I_2 \propto (a)^2$ and $I_1 \propto (2.5a)^2$

$$\therefore \frac{I_1}{I_2} = \frac{(2.5a)^2}{a^2} = (2.5)^2 = 6.25$$

In an EM wave, the magnetic field and electric field both vary sinusoidally with *x*. For a wave travelling along *x*-axis having $\vec{E}$ along *y*-axis and $\vec{B}$ along the z axis, with reference to Chapter 8, we can write E_y and B_z as

$$E_y = E_0 \sin(kx-\omega t) \quad \text{--- (13.2)}$$

and $$B_z = B_0 \sin(kx-\omega t), \quad \text{--- (13.3)}$$

where E_0 is the amplitude of the electric field E_y and B_0 is the amplitude of the magnetic field B_z. $k=\dfrac{2\pi}{\lambda}$ is the propagation constant and λ is the wavelength of the wave. $\omega = 2\pi\upsilon$ is the angular frequency of oscillations, υ being the frequency of the wave.

Both the electric and magnetic fields attain their maximum (and minimum) values at the same time and at the same point in space, i.e., $\vec{E}$ and $\vec{B}$ oscillate in phase with the same frequency.

Example 13.4: An EM wave of frequency 50 MHz travels in vacuum along the positive x-axis and $\vec{E}$ at a particular point, x and at a particular instant of time t is 9.6 $\hat{j}$ V/m. Find the magnitude and direction of $\vec{B}$ at this point x and at time t.

Solution : $B=\dfrac{E}{c}=\dfrac{9.6}{3\times10^{8}}=3.2\times10^{-8}\ \text{T}$

As the wave propagates along $+x$ axis and E is along $+y$ axis, direction of B will be along +z-axis i.e. $B = 3.2\times10^{-8}\ \hat{k}$ T.

Example 13.5: For an EM wave propagating along x direction, the magnetic field oscillates along the z-direction at a frequency of 3×10^{10} Hz and has amplitude of 10^{-9} T.

a) What is the wavelength of the wave?

b) Write the expression representing the corresponding electric field.

Solution :

a) $\lambda=\dfrac{c}{\upsilon}=\dfrac{3\times10^{8}\,\text{m/s}}{3\times10^{10}\,/\text{s}}=10^{-2}\,\text{m}$

b) $E_0 = cB_0 = (3\times10^8\ \text{m/s})\times(10^{-9}\ \text{T}) = 0.3$ V/m. Since B acts along z-axis, E acts along y-axis. Expression representing the oscillating electric field is

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

$$E_y = E_0 \sin\left[\left(\frac{2\pi}{\lambda}\right)x-(2\pi\nu)t\right]$$

$$E_y = E_0 \sin 2\pi\left[\frac{x}{\lambda}-\nu t\right]$$

$$E_y = E_0 \sin 2\pi\left[\frac{x}{10^{-2}}-3\times10^{10}t\right]$$

$$E_y = E_0 \sin 2\pi\left[100x-3\times10^{10}t\right]\ \text{V/m}$$

Example 13.6: The magnetic field of an EM wave travelling along x-axis is $\vec{B} = \hat{k}\ 4\times10^{-4}\sin(\omega t - kx)$. Here B is in tesla, t is in second and x is in m. Calculate the peak value of electric force acting on a particle of charge 5 μC travelling with a velocity of 5×10^5 m/s along the y-axis.

Solution :

$B_0 = 4\times10^{-4}$ T, $q = 5\ \mu\text{C} = 5\times10^{-6}$ C

$v = 5\times10^5$ m/s

$E_0 = cB_0 = (3\times10^8)\times(4\times10^{-4})$

$=12\times10^4$ N/C

Maximum electric force $= qE_0$

$= (5\times10^{-6})\,(12\times10^4)$

$= 60\times10^{-2}$

$= 0.6$ N

13.3 Electromagnetic Spectrum:

The orderly distribution (sequential arrangement) of EM waves according to their wavelengths (or frequencies) in the form of distinct groups having different properties is called the EM spectrum (Fig. 13.2). The properties of different types of EM waves are given in Table 13.1.

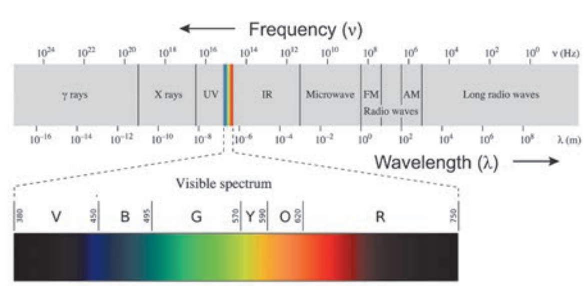

Fig. 13.2: Electromagnetic spectrum.

We briefly describe different types of EM waves in the order of decreasing wavelength (or increasing frequency).

13.3.1 Radio waves :

Radio waves are produced by accelerated motion of charges in a conducting wire. The frequency of waves produced by the circuit depends upon the magnitudes of the inductance and the capacitance (This will be discussed in XIIth standard). Thus, by choosing suitable values of the inductance and the capacitance, radio waves of desired frequency can be produced.

Properties :

1) They have very long wavelengths ranging from a few centimetres to a few hundreds of kilometres.
2) The frequency range of AM band is 530 kHz to 1710 kHz. Frequency of the waves used for TV-transmission range from 54 MHz to 890 MHz, while those for FM radio band range from 88 MHz to 108MHz.

Notation used for high frequencies
1 kHz = one kilo Hertz =1000 Hz = 10^3 Hz
1 MHz = one mega Hertz = 10^6 Hz
1 GHz = one giga Hertz =10^9 Hz
Notation used for small wavelengths
1 μm = one micrometer = 10^{-6} m
1 Å= one angstrom = 10^{-10} m= 10^{-8} cm
1nm = one nanometer = 10^{-9} m

Uses :

1) Radio waves are used for wireless communication purpose.
2) They are used for radio broadcasting and transmission of TV signals.
3) Cellular phones use radio waves to transmit voice communication in the ultra high frequency (UHF) band.

Table 13.1: Properties of different types of EM waves

Name	Wavelength range in m	Frequency range in Hz	Generated By
Gamma rays	6×10^{-13} to 1×10^{-10}	5×10^{20} to 3×10^{18}	a) Transitions of nuclear energy levels b) Radioactive substances
X-rays	1×10^{-11} to 3×10^{-8}	3×10^{19} to 1×10^{16}	a) Bombardment of high energy electrons (keV) on a high atomic number target (Cu, Mg, Co) b) Energy level transitions of innermost orbital electrons
Ultraviolet (UV waves)	3×10^{-8} to 4×10^{-7}	1×10^{16} to 8×10^{14}	Rearrangement of orbital electrons of atom between energy levels. As in high voltage gas discharge tube, the Sun and mercury vapour lamp, etc.
Visible light	4×10^{-7} to 8×10^{-7}	8×10^{14} to 4×10^{14}	Rearrangement of outer orbital electrons in atoms and molecules e.g., gas discharge tube
Infrared (IR) radiations	8×10^{-7} to 3×10^{-4}	4×10^{14} to 1×10^{12}	Hot objects
Microwaves	3×10^{-4} to 6×10^{-2}	1×10^{12} to 5×10^{9}	Special electronic devices such as klystron tube
Radio waves	6×10^{-4} to 1×10^{5}	5×10^{11} to 8×10^{10}	Acceleration of electrons in circuits

13.3.2 Microwaves :

These waves were discovered of by H. Hertz in 1888. Microwaves are produced by oscillator electric circuits containing a capacitor and an inductor. They can be produced by special vacuum tubes.

Properties

1) They heat certain substances on which they are incident.
2) They can be detected by crystal detectors.

Uses

1) Used for the transmission of TV signals.
2) Used for long distance telephone communication.
3) Microwave ovens are used for cooking.
4) Used in radar systems for the location of

distant objects like ships, aeroplanes etc,

5) They are used in the study of atomic and molecular structure.

13.3.3 Infrared waves

These waves were discovered by William Herschel (1737-1822) in 1800. All hot bodies are sources of infrared rays. About 60% of the solar radiations are infrared in nature. Thermocouples, thermopile and bolometers are used to detect infrared rays.

Properties

1) When infrared rays are incident on any object, the object gets heated.
2) These rays are strongly absorbed by glass.
3) They can penetrate through thick columns of fog, mist and cloud cover.

Uses

1) Used in remote sensing.
2) Used in diagnosis of superficial tumours and varicose veins.
3) Used to cure infantile paralysis and to treat sprains, dislocations and fractures.
4) They are used in Solar water heaters and cookers.
5) Special infrared photographs of the body called thermograms, can reveal diseased organs because these parts radiate less heat than the healthy organs.
6) Infrared binoculars and thermal imaging cameras are used in military applications for night vision.
7) Used to keep green house warm.
8) Used in remote controls of TV, VCR, etc

13.3.4 Visible light :

It is the most familiar form of EM waves. These waves are detected by human eye. Therefore this wavelength range is called the visible light. The visible light is emitted due to atomic excitations.

Properties :

1) Different wavelengths give rise to different colours. These are given in Table 13.2.
2) Visible light emitted or reflected from objects around us provides us information about those objects and hence about the surroundings.

Do you know ?

Stars and galaxies emit different types of waves. Radio waves and visible light can pass through the Earth's atmosphere and reach the ground without getting absorbed significantly. Thus the radio telescopes and optical telescopes can be placed on the ground. All other type of waves get absorbed by the atmospheric gases and dust particles. Hence, the γ-ray, X-ray, ultraviolet, infrared, and microwave telescopes are kept aboard artificial satellites and are operated remotely from the Earth. Even though the visible radiation reaches the surface of the Earth, its intensity decreases to some extent due to absorption and scattering by atmospheric gases and dust particles. Optical telescopes are therefore located at higher altitudes.

The Indian Giant Metrewave Radio Telescope (GMRT) near Pune is an important milestone in the field of Radio-astronomy. Also, Indian Astronomical Observatory houses the Himalayan Chandra Telescope (HCT), the 2 m optical-IR Telescope, which is situated at Hanle, Ladakh, at an altitude of 4500 m.

Table 13.2: Wavelengths of colours in visible light

Colour	Wavelength
violet	380-450 nm
blue	450-495 nm
green	495-570 nm
yellow	570-590 nm
orange	590-620 nm
red	620-750 nm

13.3.5 Ultraviolet rays :

Ultraviolet rays were discovered by J. Ritter (1776-1810) in 1801. They can be produced by the mercury vapour lamp, electric spark and carbon arc lamp. They can also be obtained by striking electrical discharge in hydrogen and xenon gas tubes. The Sun is the most important natural source of ultraviolet rays, most of which are absorbed by the ozone layer in the Earth's atmosphere.

Properties :

1) They produce fluorescence in certain materials, such as 'phosphors'.
2) They cause photoelectric effect.
3) They cannot pass through glass but pass through quartz, fluorite, rock salt etc.
4) They possess the property of synthesizing vitamin D, when skin is exposed to them.

Uses :

1) Ultraviolet rays destroy germs and bacteria and hence they are used for sterilizing surgical instruments and for purification of water.
2) Used in burglar alarms and security systems.
3) Used to distinguish real and fake gems.
4) Used in analysis of chemical compounds.
5) Used to detect forgery.

Do you know ?

1. A fluorescent light bulb is coated from with a powder inside and contains a gas; electricity causes the gas to emit ultraviolet radiation, which then stimulates the tube coating to emit light.
2. The pixels of a television or computer screen fluoresce when electrons from an electron gun strike them.
3. What we call 'visible light' is just the part of the EM spectrum that human eyes see. Many other animals would define 'visible' somewhat differently. For instance, many animals including insects and birds, see in the UV region. Natural world is full of signals that animals see and humans cannot. Many birds including bluebirds, budgies, parrots and even peacocks have ultraviolet patterns that make them even more vivid to each other than they are to us.

13.3.6 *X*-rays:

German physicist W. C. Rontgen (1845-1923) discovered *X*-rays in 1895 while studying cathode rays (which is a stream of electrons emitted by the cathode in a vacuum tube). *X*-rays are also called Rontgen rays. *X*-rays are produced when cathode rays are suddenly stopped by an obstacle.

Properties

1) They are high energy EM waves.
2) They are not deflected by electric and magnetic fields.
3) X-rays ionize the gases through which they pass.
4) They have high penetrating power.
5) Their over dose can kill living plant and animal overdose tissues and hence are harmful.

Uses

1) Useful in the study of the structure of crystals.
2) X-ray photographs are useful to detect bone fracture. X-rays have many other medical uses such as CT scan.
3) X-rays are used to detect flaws or cracks in metals.
4) These are used for detection of explosives, opium etc.

13.3.7 Gamma Rays (γ-rays)

Discovered by P. Villard (1860-1934) in 1900. Gamma rays are emitted from the nuclei of some radioactive elements such as uranium, radium etc.

Properties

1) They are highest energy EM waves. (energy range keV - GeV)
2) They are highly penetrating.
3) They have a small ionising power.
4) They kill living cells.

Uses

1) Used as insecticide disinfection for wheat and flour.
2) Used for food preservation.
3) Used in radiotherapy for the treatment of cancer and tumour.
4) They are used to produce nuclear reactions.

13.4 Propagation of EM Waves:

You must have seen a TV antenna used to receive the TV signals from the transmitting tower or from a satellite. In communication using radio waves, an antenna in the transmitter radiates the EM waves, which travel through space and reach the receiving antenna at the other end. As the EM wave travels away from the transmitter; the strength of the wave keeps on decreasing. Several factors influence the propagation of EM waves and the path they follow. It is also important to understand the composition of the Earth's atmosphere as it plays a vital role in the propagation of EM waves. Different layers of Earth's atmosphere are shown in Fig. 13.3.

Do you know ?

Ionizing radiations :

Ultraviolet, *X*-ray and gamma rays have sufficient energy to cause ionization i.e. they strip electrons from atoms and molecules lying along their path. The atoms lose their electrons and are then known as ions. Ionization is harmful to human beings because it can kill or damage living cells, or make them grow abnormally as cancers. Fluorescent lamps are based on ionization of gas. Ionizing radiation is also used in various equipments in laboratory and industry.

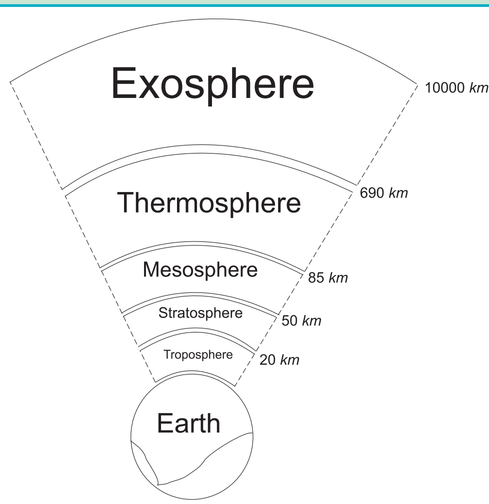

Fig 13.3: Earth and atmospheric layers.

Different modes of propagation of EM waves are described below and are shown in Fig. 13.4.

Do you know ?

X-rays have many practical applications in medicine and industry. Because *X*-ray photons are of such high energy, they can penetrate several centimetres of solid matter and can be used to visualize the interiors of materials that are opaque to ordinary light.

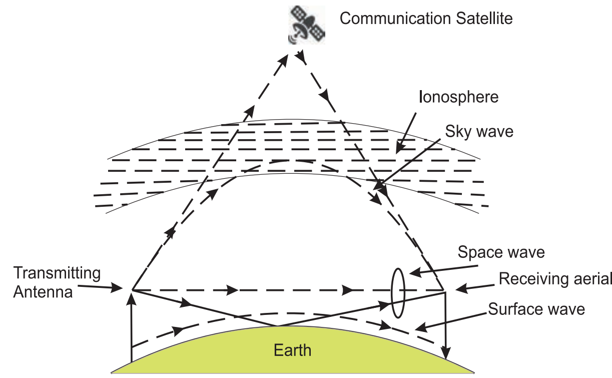

Fig. 13.4: Propagation of EM waves.

13.4.1 Ground (surface) wave:

When a radio wave from a transmitting antenna propagates near surface of the Earth so as to reach the receiving antenna, the wave propagation is called ground wave or surface wave propagation.

In this mode, radio waves travel close to the surface of the Earth and move along its curved surface from transmitter to receiver.

The radio waves induce currents in the ground and lose their energy by absorption. Therefore, the signal cannot be transmitted over large distances. Radio waves having frequency less than 2 MHz (in the medium frequency band) are transmitted by ground wave propagation. This is suitable for local broadcasting only. For TV or FM signals (very high frequency), ground wave propagation cannot be used.

13.4.2 Space wave:

When the radio waves from the transmitting antenna reach the receiving antenna either directly along a straight line (line of sight) or after reflection from the ground or satellite or after reflection from troposphere, the wave propagation is called space wave propagation. The radio waves reflected from troposphere are called tropospheric waves. Radio waves with frequency greater than 30 MHz can pass through the ionosphere (60 km - 1000 km) after suffering a small deviation. Hence, these waves cannot be transmitted by space wave propagation except by using a satellite. Also, for TV signals which have high frequency, transmission over long distance is not possible by means of space wave propagation.

The maximum distance over which a signal can reach is called its range. For larger TV coverage, the height of the transmitting antenna should be as large as possible. This is the reason why the transmitting and receiving antennas are mounted on top of high rise buildings.

Range is the straight line distance from the point of transmission (the top of the antenna) to the point on Earth where the wave will hit while travelling along a straight line. Range is shown by d in Fig. 13.5. Let the height of the transmitting antenna (AA') situated at A be h. B represents the point on the surface of the Earth at which the space wave hits the Earth. The triangle OA'B is a right angled triangle. From Δ OA' B we can write

$$OA'^2 = A'B^2 + OB^2$$

$$(R+h)^2 = d^2 + R^2$$

or $R^2 + h^2 + 2Rh = d^2 + R^2$

As $h << R$, we can ignore h^2 and write

$$d \cong \sqrt{2Rh}$$

The range can be increased by mounting the receiver at a height h' say at a point C on the surface of the Earth. The range increases to $d + d'$ where d' is $\sqrt{2Rh'}$ Thus

$$\text{Total range} = d + d' = \sqrt{2Rh} + \sqrt{2Rh'}$$

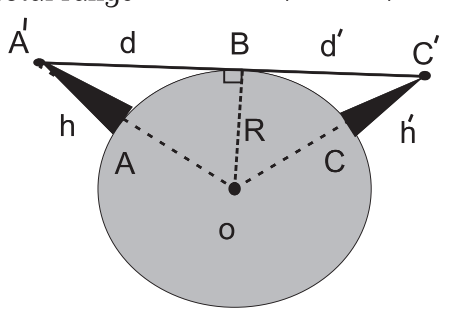

Fig. 13.5: Range of the signal (not to scale).

Example 13.7: A radar has a power of 10 kW and is operating at a frequency of 20 GHz. It is located on the top of a hill of height 500 m. Calculate the maximum distance upto which it can detect object located on the surface of the Earth . (Radius of Earth = 6.4×10^6 m)

Solution:

Maximum distance (range) =

$$d = \sqrt{2Rh}$$

$$= \sqrt{2\times(6.4\times10^6)\times500}\ \text{m}$$

$$= 8\times10^4 = 80\ \text{km},$$

where R is radius of the Earth and h is the height of the radar above Earth's surface.

Example 13.8: If the height of a TV transmitting antenna is 128 m, how much square area can be covered by the transmitted signal if the receiving antenna is at the ground level? (Radius of the Earth = 6400 km)

Solution:

$$\text{Range} = d = \sqrt{2Rh}$$

$$= \sqrt{2(6400\times10^3)(128)}$$

$$= \sqrt{16.384\times10^5\times10^3}$$

$$= \sqrt{16.384\times10^8}$$

$$= 4.047\times10^4$$

$$= 40.470\ \text{km}$$

$$\text{Area covered} = \pi d^2 = 3.14\times(40)^2$$

$$= 5144.58\ \text{k4m}^2$$

Example 13.9: The height of a transmitting antenna is 68 m and the receiving antenna is at the top of a tower of height 34 m. Calculate the maximum distance between them for satisfactory transmission in line of sight mode. (radius of Earth = 6400 km)

$h_t = 68$ m, $h_r = 34$m, $R = 6400$ km $= 6.4\times10^6$m

Solution:

$$d_{max} = \sqrt{2Rh_t} + \sqrt{2Rh_r}$$

$$= \sqrt{2\times6.4\times10^6\times68} + \sqrt{2\times6.4\times10^6\times34}$$

$$= \sqrt{870}\times10^3 + \sqrt{435}\times10^3$$

$$= 29.5\times10^3 + 20.9\times10^3$$

$$= 50.4\times10^3\ \text{m}$$

$$= 50.4\ \text{km}$$

13.4.3 Sky wave propagation:

When radio waves from a transmitting antenna reach the receiving antenna after reflection in the ionosphere, the wave propagation is called sky wave propagation.

The sky waves include waves of frequency between 3 MHz and 30 MHz. These waves can suffer multiple reflections between the ionosphere and the Earth. Therefore, they can be transmitted over large distances.

Critical frequency : It is the maximum value of the frequency of radio wave which can be reflected back to the Earth from the ionosphere when the waves are directed normally to ionosphere.

Skip distance (zone) : It is the shortest distance from a transmitter measured along the surface of the Earth at which a sky wave of fixed frequency (if grater than critical frequency) will be returned to the Earth so that no sky waves can be received within the skip distance.

13.5 Introduction to Communication System:

Communication is exchange of information. Since ancient times it is practiced in various ways e.g., through speaking, writing, singing, using body language etc. After the discovery of electricity in the late 19^{th} century, human communication systems changed dramatically. Modern communication is based upon the discoveries and inventions by a number of scientists like J. C. Bose (1858-1937), S. F. B. Morse (1791-1872), G. Marconi (1874-1937) and Alexander Graham Bell (1847-1922) in the 19^{th} and 20^{th} centuries.

In the 20^{th} century we could send messages over large distances using analogue signals, cables and radio waves. With the advancements of digitization technologies, we can now communicate with the entire world almost in real time.

The ability to communicate is an important feature of modern life. We can speak directly to others all around the world and generate vast amount of information every day.

Here we will briefly discuss how communication systems work. A communication system is a device or set up used in transmission and reception of information from one place to another.

13.5.1 Elements of a communication system:

There are three basic (essential) elements of every communication system: a) Transmitter, b) Communication channel and c) Receiver.

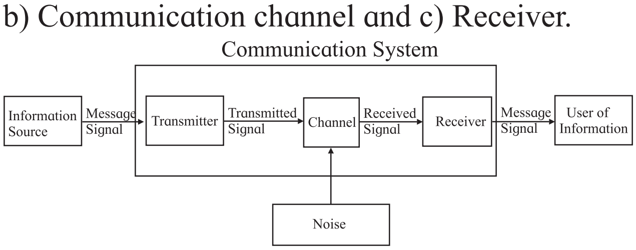

Fig. 13.6: Block diagram of the basic elements of a communication system.

In a communication system, as shown in Fig. 13.6, the transmitter is located at one place and the receiver at another place. The communication channel is a passage through which signals transfer in between a transmitter and a receiver. This channel may be in the form of wires or cables, or may also be wireless, depending on the types of communication system.

There are two basic modes of communication: (i) point to point communication and (ii) broadcast.

In point to point communication mode, communication takes place over a link between a single transmitter and a receiver e.g. Telephony. In the broadcast mode there are large number of receivers corresponding to the single transmitter e.g., Radio and Television transmission.

13.5.2 Commonly used terms in electronic communication system:

Following terms are useful to understand any communication system:

1) Signal :- The information converted into electrical form that is suitable for transmission is called a signal. In a radio station, music and speech are converted into electrical form by a microphone for transmission into space. This electrical form of sound is the signal. A signal can be analog or digital as shown in Fig. 13.7.

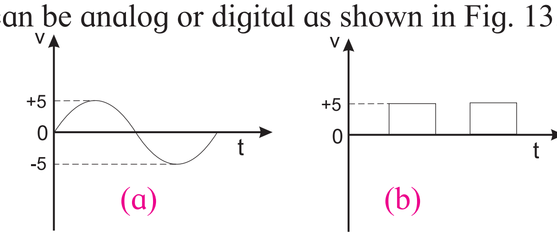

Fig 13.7: (a) Analog signal. (b) Digital signal.

(i) Analog signal: A continuously varying signal (voltage or current) is called an analog signal. Since a wave is a fundamental analog signal, sound and picture signals in TV are analog in nature (Fig 13.7 a)

(ii) Digital signal : A signal (voltage or current) that can have only two discrete values is called a digital signal. For example, a square wave is a digital signal. It has two values viz, +5 V and 0 V. (Fig- 13.7 b)

2) Transmitter :- A transmitter converts the signal produced by a source of information into a form suitable for transmission through a channel and subsequent reception.

3) Transducer :- A device that converts one form of energy into another form of energy is called a transducer. For example, a microphone converts sound energy into electrical energy. Therefore, a microphone is a transducer. Similarly, a loudspeaker is a transducer which converts electrical energy into sound energy.

4) Receiver :- The receiver receives the message signal at the channel output, reconstructs it in recognizable form of the original message for delivering it to the user of information.

5) Noise :- A random unwanted signal is called noise. The source generating the noise may be located inside or outside the system. Efforts should be made to minimise the noise level in a communication system.

6) Attenuation :- The loss of strength of the signal while propagating through the channel is known as attenuation. It occurs because the channel distorts, reflects and refracts the signals as it passes through it.

7) Amplification :- Amplification is the process of raising the strength of a signal, using an electronic circuit called amplifier.

8) Range :- The maximum (largest) distance between a source and a destination up to which the signal can be received with sufficient strength is termed as range.

9) Bandwidth :- The bandwidth of an electronic circuit is the range of frequencies over which it operates efficiently.

10) Modulation :- The signals in communication system (e.g. music, speech etc.) are low frequency signals and cannot be transmitted over large distances. In order to transmit the signal to large distances, it is superimposed on a high frequency wave (called carrier wave). This process is called modulation. Modulation is done at the transmitter and is an important part of a communication system.

11) Demodulation :- The process of regaining signal from a modulated wave is called demodulation. This is the reverse process of modulation.

12) Repeater :- It is a combination of a transmitter and a receiver. The receiver receives the signal from the transmitter, amplifies it and transmits it to the next repeater. Repeaters are used to increase the range of a communication system. These are shown in Fig. 13.8.

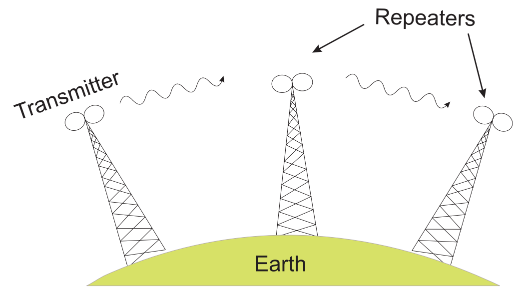

Fig.13.8: Use of repeater station to increase the range of communication.

Do you know ?

To transmit a signal we need an antenna or an aerial. For efficient transmission and reception, the transmitting and receiving antennas must have a length at least $\lambda/4$ where λ is the wavelength of the signal.

For an audio signal of 15kHz, the required length of the antenna is $\lambda/4$ which can be seen to be equal to 5 km.

The highest TV tower in Rameshwaram, Tamilnadu, is the tallest tower in India and is ranked 32nd in the world with pinnacle height of 323 metre. It is used for television broadcast by the Doordarshan.

13.6 Modulation:

As mentioned earlier, an audio signal has low frequency (< 20 KHz). Low frequency signals can not be transmitted over large distances. Because of this, a high frequency wave, called a carrier wave, is used. Some characteristic (e.g. amplitude, frequency or phase) of this wave is changed in accordance with the amplitude of the signal. This process is known as modulation. Modulation also helps avoid mixing up of signals from different transmitters as different carrier wave frequencies can be allotted to different transmitters. Without the use of these waves, the audio signals, if transmitted directly by different transmitters, would have got mixed up.

Modulation can be done by modifying the (i) amplitude (amplitude modulation) (ii) frequency (frequency modulation), and (iii) phase (phase modulation) of the carrier wave in proportion to the amplitude or intensity of the signal wave keeping the other two properties same. Figure 13.9 (a) shows a carrier wave and (b) shows the signal. The carrier wave is a high frequency wave while the signal is a low frequency wave. Amplitude modulation, frequency modulation and phase modulation of carrier waves are shown in Fig. 13.9 (c), (d) and (e) respectively.

Amplitude modulation (AM) is simple to implement and has large range. It is also cheaper. Its disadvantages are that (i) it is not very efficient as far as power usage is concerned (ii) it is prone to noise and (iii) the reproduced signal may not exactly match the original signal. In spite of this, these are used for commercial broadcasting in the long, medium and short wave bands.

Frequency modulation (FM) is more complex as compared to amplitude modulation and, therefore is more difficult to implement. However, its main advantage is that it reproduces the original signal closely and is less susceptible to noise. This modulation is used for high quality broadcast transmission.

Phase modulation (PM) is easier than frequency modulation. It is used in determining the velocity of a moving target which cannot be done using frequency modulation.

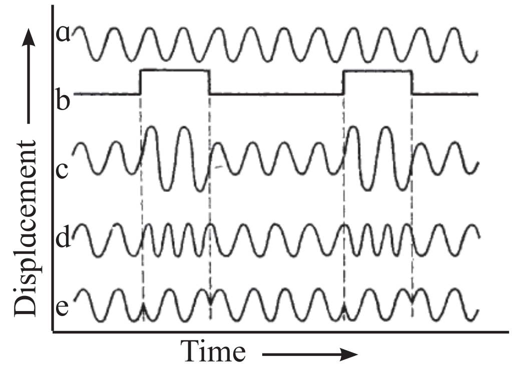

Fig. 13.9: (a) Carrier wave, (b) signal (c) AM (d) FM and (e) PM.

Internet my friend

https://www.iiap.res.in/centers/iao

Exercises

1. Choose the correct option.

i) The EM wave emitted by the Sun and responsible for heating the Earth's atmosphere due to green house effect is

(A) Infra-red radiation (B) X ray
(C) Microwave (D) Visible light

ii) Earth 's atmosphere is richest in

(A) UV (B) IR
(C) X-ray (D) Microwaves

iii) How does the frequency of a beam of ultraviolet light change when it travels from air into glass?

(A) No change (B) increases
(C) decreases (D) remains same

iv) The direction of EM wave is given by

(A) $\vec{E} \times \vec{B}$ (B) $\vec{E} \cdot \vec{B}$
(C) along $\vec{E}$ (D) along $\vec{B}$

v) The maximum distance upto which TV transmission from a TV tower of height h can be received is proportional to

(A) $h^{1/2}$ (B) h
(C) $h^{3/2}$ (D) h^2

vi) The waves used by artificial satellites for communication purposes are

(A) Microwave
(B) AM radio waves
(C) FM radio waves
(D) X-rays

vii) If a TV telecast is to cover a radius of 640 km, what should be the height of transmitting antenna?

(A) 32000 m (B) 53000 m
(C) 42000 m (D) 55000 m

2. Answer briefly.

i) State two characteristics of an EM wave.

ii) Why are microwaves used in radar?

iii) What are EM waves?

iv) How are EM waves produced?

v) Can we produce a pure electric or magnetic wave in space? Why?

vi) Does an ordinary electric lamp emit EM waves?

vii) Why do light waves travel in vacuum whereas sound wave cannot?

viii) What are ultraviolet rays? Give two uses.

ix) What are radio waves? Give its two uses.

x) Name the most harmful radiation entering the Earth's atmosphere from the outer space.

xi) Give reasons for the following:
(i) Long distance radio broadcast uses short wave bands.
(ii) Satellites are used for long distance TV transmission.

xii) Name the three basic units of any communication system.

xiii) What is a carrier wave?

xiv) Why high frequency carrier waves are used for transmission of audio signals?

xv) What is modulation?

xvi) What is meant by amplitude modulation?

xvii) What is meant by noise?

xviii) What is meant by bandwidth?

xix) What is demodulation?

xx) What type of modulation is required for television broadcast?

xxi) How does the effective power radiated by an antenna vary with wavelength?

xxii) Why should broadcasting programs use different frequencies?

xxiii) Explain the necessity of a carrier wave in communication.

xxiv) Why does amplitude modulation give noisy reception?

xxv) Explain why is modulation needed.

2. Solve the numerical problem.

i) Calculate the frequency in MHz of a radio wave of wavelength 250 m. Remember that the speed of all EM waves in vacuum is 3.0×10^8 m/s.

[Ans: 1.2 MHz]

ii) Calculate the wavelength in nm of an X-ray wave of frequency 2.0×10^{18} Hz.

[Ans: 0.15 nm]

iii) The speed of light is 3×10^8 m/s. Calculate the frequency of red light of wavelength of 6.5×10^{-7} m.

[Ans: $\upsilon = 4.6\times10^{14}$ Hz]

iv) Calculate the wavelength of a microwave of frequency 8.0 GHz.

[Ans: 3.75 cm]

v) In a EM wave the electric field oscillates sinusoidally at a frequency of 2×10^{10} Hz. What is the wavelength of the wave?

[Ans: 1.5×10^{-2} m]

vi) The amplitude of the magnetic field part of a harmonic EM wave in vacuum is $B_0= 5\times10^{-7}$ T. What is the amplitude of the electric field part of the wave?

[Ans: 150V/m]

vii) A TV tower has a height of 200 m. How much population is covered by TV transmission if the average population density around the tower is 1000/km^2? (Radius of the Earth = 6.4×10^6 m)

[Ans: 8×10^6]

viii) Height of a TV tower is 600 m at a given place. Calculate its coverage range if the radius of the Earth is 6400 km. What should be the height to get the double coverage area?

[Ans: 87.6 km, 1200 m]

ix) A transmitting antenna at the top of a tower has a height 32 m and that of the receiving antenna is 50 m. What is the maximum distance between them for satisfactory communication in line of sight mode ? Given radius of Earth is 6.4×10^6 m.

[Ans: 45.537 km]

***