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ELECTROMAGNETIC WAVES

3.1 Introduction

Dear friends, when you wake up in the morning, you would have seen the golden (yellow – orange) sun rising from the East. Further you could have observed colourful flowers on green plants–trees and colourful birds in the sky. How can we see such things ? You would say that we can see by our eyes and our mind analyzes that picture. But how do our eyes see ? This is dependent upon the electromagnetic waves. Our eyes can see the picture in terms of electromagnetic waves. The visible radiations (and other radiations) produced from the sun reach the earth. Animals–birds, fruits–flowers etc. reflect electromagnetic waves of different wavelengths (or frequencies) corresponding to their colours, due to which we can see the respective colours of the objects.

In nineteenth century, the great scientist Maxwell presented the laws of electricity and magnetism; like Gauss's law, Ampere's law, Faraday's law, and the formation of closed loops by the magnetic field, in the form of differential equations. This lead to the concept of the electromagnetic waves. While examining the symmetry between (consistency among) the differential equations for the electric and magnetic fields, it was observed that some term was missing in equation of Ampere's law. Maxwell postulated the missing term in terms of the displacement current. Now the resulting differential equations for electric field $\vec{E}$ and magnetic field $\vec{B}$ were identical with the wave equations. Not only this, but from these wave equations it was established that the velocity of these waves is equal to the velocity of light in vacuum. This established the fact that light waves are nothing but the waves associated with electric field $\vec{E}$ and magnetic field $\vec{B}$ i.e., electromagnetic waves.

Displacement Current : Apart from curing the defect in Ampere's law, Maxwell's term has a certain aesthetic appeal. Just as a changing magnetic field induces electric field (Faraday's law) similarly a changing electric field induces a magnetic field. The real confirmation of Maxwell's theory came in 1887 with Hertz's experiments on electromagnetic radiation.

In Ampere's law, according to Maxwell's opinion,

$$\oint \vec{B} \cdot \vec{dl} = \mu_0 i + ?$$

Maxwell called this missing term as displacement current.

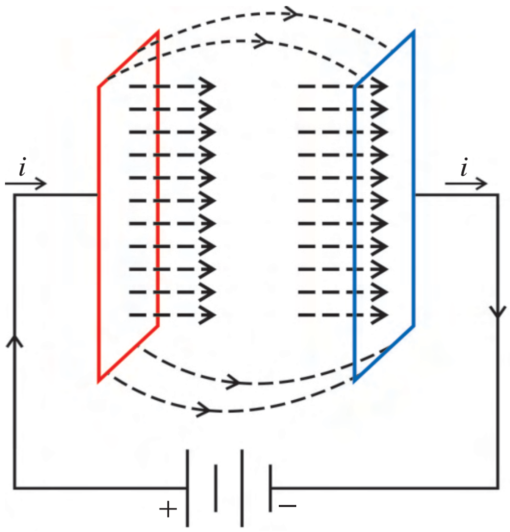


Figure 3.1 A Simple Capacitor Circuit

What exactly is implied (meant) by the displacement current ? This displacement current does not have the significance of a current in the sense of being the motion of charges. It can be clearly demonstrated by considering a simple capacitor circuit as shown in figure 3.1.

A current i enters the positive plate and leaves the negative plate of a parallel plate capacitor.

This current cannot continue for longer time. When the capacitor becomes fully charged the current becomes zero. If the capacitor plates are very close together then the field between them is,

$$E = \frac{1}{\varepsilon_0}\sigma = \frac{1}{\varepsilon_0}\frac{Q}{A}$$

Where, Q is the charge on the plate, and A is its area. Thus, when the capacitor is getting charged between the plates

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

$$\therefore \ \varepsilon_0 \frac{\partial E}{\partial t} = \frac{i}{A} = J_d$$

$\therefore \ \varepsilon_0 A \frac{\partial E}{\partial t} = i_d$ which is called the displacement current.

In integral form,

$$\varepsilon_0 \int \frac{\partial \vec{E}}{\partial t} \cdot \vec{da} = i_d$$

Adding integral form of displacement current in Ampere's law

$$\oint \vec{B} \cdot \vec{dl} = \mu_0 i_c + \mu_0 \varepsilon_0 \int \frac{\partial \vec{E}}{\partial t} \cdot \vec{da}$$

or $\oint \vec{B} \cdot \vec{dl} = \mu_0 i_c + \mu_0 i_d = \mu_0 (i_c + i_d)$

This equation is known as Ampere-Maxwell law, which shows that 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. Out side the capacitor plates, there is only conduction current and inside the capacitor, there is only displacement current.

Maxwell's Equations (For Information Only)

(1) $\oint \vec{E} \cdot \vec{da} = \frac{q}{\varepsilon_0}$ (Gauss's law for electricity)

(2) $\oint \vec{B} \cdot \vec{da} = 0$ (Gauss's law for magnetisam)

(3) $\oint \vec{E} \cdot \vec{dl} = \frac{-d\phi_B}{dt}$ (Faraday's law)

(4) $\oint \vec{B} \cdot \vec{dl} = \mu_0 (i_c + i_d)$ (Ampere–Maxwell law)

Where, i_c = conduction current, and

$i_d = \varepsilon_0 \int \frac{\partial \vec{E}}{\partial t} \cdot \vec{da}$ = displacement current

3.2 Transverse nature of Electromagnetic Waves

After the mathematical representation of electromagnetic waves by Maxwell, it took time before the experimental confirmation was established. After about 32 years Hertz gave the proof for the existence of electromagnetic waves in the laboratory.

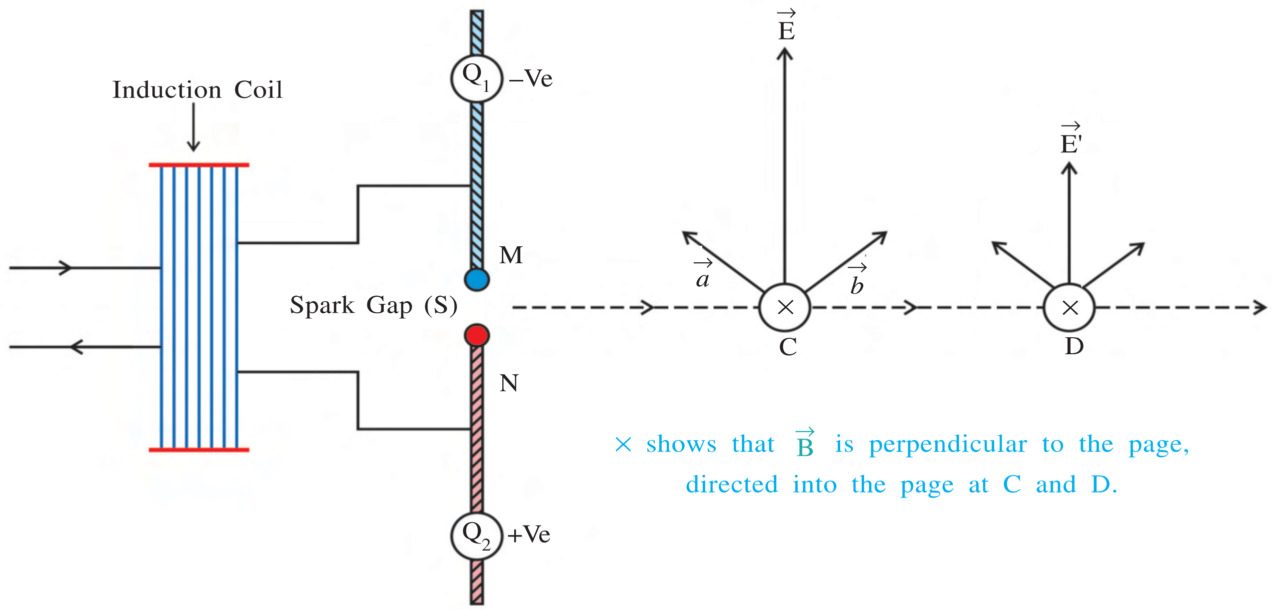


Figure 3.2 A Simple Arrangement of Hertz's Experiment

As shown in figure 3.2, two metallic spheres Q_1 and Q_2 are connected by means of metallic rods M and N, and a spark gap S is formed between the two rods. Spark can be produced in the spark gap by applying a large potential difference between the rods using an induction coil. The spheres Q_1 and Q_2 constitute a capacitor, while the rods behave as an inductor. Such an arrangement can be considered equivalent to L–C oscillator circuit, and known as Hertzian Dipole. At a moment, when one sphere Q_1 is negatively charged and Q_2 is positively charged, the electric field produced at points C and D is shown in the figure. When the spark is produced, the electrons pass from sphere Q_1 towards Q_2 through the spark gap S. This electron current induces magnetic field at points C and D as shown in the figure 3.2. When spark passes, the sphere Q_1 becomes less negative and sphere Q_2 becomes less positive with time, and then after some time the polarity on the spheres Q_1 and Q_2 is reversed, and so on. This process keeps on repeating in a fixed time interval.

Thus, oscillating charges are responsible for the generation of periodically varying electric field in the space. Further, the oscillating charges generate varying electric current which in turn is responsible for the generation of periodically varying magnetic field. (It can be found from the Ampere's right hand rule that the induced magnetic field is perpendicular to the electric field). This way the electromagnetic waves are generated. The frequency of the generated electromagnetic waves is equal to the frequency of oscillation of the electric charges. The frequency of these waves can be varied by changing the distance between the spheres. In the case of electromagnetic waves,

$$c \text{ (velocity)} = \lambda \text{ (wavelength)} \times f \text{ (frequency)}$$

Seven years after the Hertz's experiment Jagdishchandra Bose generated electromagnetic waves having the wavelength in the range of 5 mm to 25 mm. Almost during the same time, an Italian scientist Marconi succeeded in the transmission of electromagnetic waves upto a distance of several miles.

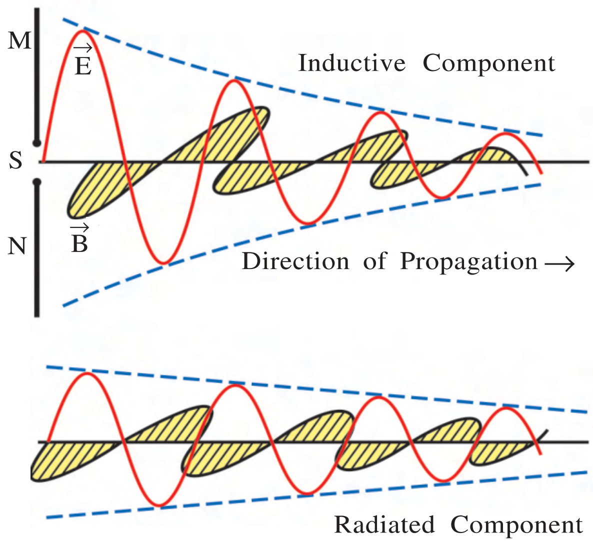


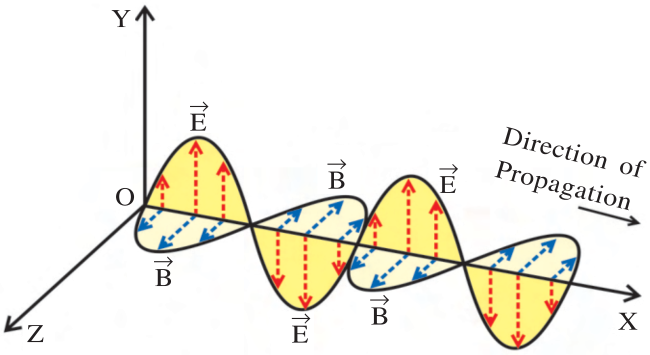
Figure 3.3 Electric and Magnetic Fields at any Instant

According to Maxwell's theory, these electric and magnetic fields do not come into existence instantaneously. In the region closer to the oscillating charges, the phase difference between $\vec{E}$ and $\vec{B}$ fields is $\frac{\pi}{2}$ and their magnitude quickly decreases as $\frac{1}{r^3}$ (where r = the distance from the source). These components of the transmitted waves near their origin (or fields) are called Inductive Components (See figure 3.3).

At large distances $\vec{E}$ and $\vec{B}$ are in phase and the decrease in their magnitude is comparatively slower with distance, as per $\frac{1}{r}$. These components of electromagnetic radiation are called Radiated Components.

When an elctromagnetic wave passes through any point in the space, the electric field and magnetic field vectors oscillate in mutually perpendicular planes, perpendicular to the direction of propagation of the wave at that point (See figure 3.4)

Suppose $\vec{E}$ and $\vec{B}$ are zero at some point away from the origin at any instant of time. As the time passes, the values of $\vec{E}$ and $\vec{B}$ increase with time, reach a maximum value and then start decreasing again to become zero. After that the direction of the fields are reversed. Now the fields start to increase in this reversed direction, reach maximum value and then again decrease to become zero. This process continues periodically as long as the electromagnetic waves pass through that point. This is the meaning of 'oscillating electric and magnetic fields'. The energy of the electromagnetic waves is equal to the kinetic energy of the charges oscillating between the two spheres.



Note : direction of propagation is that of $\vec{E} \times \vec{B}$

Figure 3.4

3.3 Characteristics of Electromagnetic Waves

In figure 3.4 we saw an electromagnetic wave propagating along the X–direction. Here electric field $\vec{E}$ lies in X–Y plane and is parallel to Y–axis, whereas magnetic field $\vec{B}$ lies in X–Z plane and is parallel to Z–axis. The characteristics of electromagnetic waves are like this :

(1) Representation in the Form of Equations : For the electromagnetic wave shown in figure 3.4 at time t, the y component (E_y) of electric field varies according to sine function, whereas its E_x and E_z components are zero. Hence the equation for the E_y component is

$$E_y = E_0 \sin(\omega t - kx) \tag{3.3.1}$$

which in vector form is

$$\vec{E} = E_y \hat{j} = [E_0 \sin(\omega t - kx)]\, \hat{j} \tag{3.3.2}$$

where ω = angular frequency, and $k = \frac{2\pi}{\lambda}$ = magnitude of wave vector. $\vec{k}$ is in the direction of propagation of the wave.

The speed of propagating wave is $c = \frac{\omega}{k}$

Similarly, as $B_x = B_y = 0$, the component B_z of magnetic field is

$$\vec{B} = B_z \hat{k} = [B_0 \sin(\omega t - kx)]\hat{k} \tag{3.3.3}$$

(2) In electromagnetic wave the relation between the magnitudes of $\vec{E}$ and $\vec{B}$ is $\frac{E}{B} = c.$

Here, remember that the electromagnetic waves are self sustaining oscillations of electric and magnetic fields in free space, or vacuum.

In the region far away from the source, electric and magnetic fields oscillate in phase.

The constituent particles of material medium are not oscillating with the vibrations of electric and magnetic fields. It means that they are non-mechanical waves.

(3) The velocity of the electromagnetic waves in vacuum (free space) is

$$c = \frac{1}{\sqrt{\mu_0 \varepsilon_0}} \tag{3.3.4}$$

This fact was derived for the first time by Maxwell, using the equations for the electric and magnetic fields. Here,

$\mu_0 = 4\pi \times 10^{-7}$ N A^{-2} = permeability of free space,

$\varepsilon_0 = 8.85419 \times 10^{-12}$ C^2 N^{-1} m^{-2} = permittivity of free space, and

$c = 2.99792 \times 10^8$ ms^{-1}. This value is equal to the magnitude of velocity of light in vacuum.

The velocity of the electromagnetic waves propagating through any medium is given by

$$v = \frac{1}{\sqrt{\mu\varepsilon}} \tag{3.3.5}$$

where, μ = permeability of the medium, and ε = permittivity of the medium.

Thus, the velocity of light depends on electric and magnetic properties of the medium. Now, for any medium, relative permeability $\mu_r = \frac{\mu}{\mu_0}$ and, relative permittivity $\varepsilon_r = \frac{\varepsilon}{\varepsilon_0} = K$

where, K = dielectric constant of the medium.

Hence, from equation (3.3.5)

$$v = \frac{1}{\sqrt{\mu_0 \mu_r \varepsilon_0 \varepsilon_r}} = \frac{1}{\sqrt{\mu_0 \varepsilon_0}} \frac{1}{\sqrt{\mu_r \varepsilon_r}} = \frac{c}{\sqrt{\mu_r \varepsilon_r}} = \frac{c}{\sqrt{\mu_r K}} \tag{3.3.6}$$

Therefore, the refractive index of the medium is

$$n = \frac{c}{v} = \sqrt{\mu_r \varepsilon_r} = \sqrt{\mu_r K} \tag{3.3.7}$$

The velocity of electromagnetic waves in free space or vacuum is an important fundamental constant.

(4) Electromagnetic waves are transverse waves.

(5) Electromagnetic waves possess energy, and they can carry energy from one place to the other. Electromagnetic waves carry energy from the Sun to the earth, thus making the life possible on the earth.

(6) Electromagnetic waves exert pressure on a surface when they are incident on it, called radiation pressure. This imparts linear momentum to the surface.

If ΔU is the energy of electromagnetic waves incident on a surface of area A in Δt time, normal to the direction of flow of energy, then assuming that the energy is completely absorbed, the momentum delivered to this surface is

$$\Delta p = \frac{\Delta U}{c} \text{ (for complete absorption)}$$

$$\text{and } \Delta p = 2\frac{\Delta U}{c} \text{ (for complete reflection)} \qquad (3.3.8)$$

which also exerts the radiation pressure (P_S) on the surface.

(7) Electromagnetic fields are prevalent in region where the electromagnetic waves propagate. The electromagnetic energy per unit volume (energy density) in a region is given by

$$\rho = \rho_E + \rho_B = \frac{1}{2}\varepsilon_0 E^2 + \frac{B^2}{2\mu_0} \qquad (3.3.9)$$

where ρ_E = energy density associated with electric field, and ρ_B = energy density associated with magnetic field.

We obtained these relations for capacitor and inductor, in case of stationary fields. In the case of electromagnetic waves, the $\vec{E}$ and $\vec{B}$ fields are oscillating as per sine or cosine functions. Hence, we have to replace E and B in equation (3.3.9) by E_{rms} and B_{rms} to calculate the energy density for electromagnetic waves.

$$\therefore \rho = \frac{1}{2}\varepsilon_0 E^2_{rms} + \frac{B^2_{rms}}{2\mu_0} \qquad (3.3.10)$$

$$\text{Now, } c^2 = \frac{1}{\varepsilon_0\mu_0} \Rightarrow \mu_0 = \frac{1}{\varepsilon_0 c^2}$$

$$\text{Also, } B_{rms} = \frac{E_{rms}}{c}$$

$$\therefore \rho = \frac{1}{2}\varepsilon_0 E^2_{rms} + \frac{\frac{E^2_{rms}}{c^2}}{\frac{2}{\varepsilon_0 c^2}} = \frac{1}{2}\varepsilon_0 E^2_{rms} + \frac{1}{2}\varepsilon_0 E^2_{rms}$$

$$\therefore \rho = \varepsilon_0 E^2_{rms} \qquad (3.3.11)$$

Similarly we can obtain $\rho = \frac{B_{rms}^2}{\mu_0}$

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

$$I = \frac{\text{Energy/time}}{\text{Area}} = \frac{\text{Power}}{\text{Area}}$$

Figure 3.5 shows the radiation energy passing through a unit cross sectional area in one second confined within a volume of length equal to c. If ρ is the energy density, then the energy in the above volume is $\rho.c$.

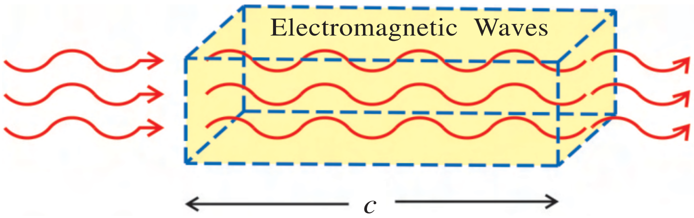


Figure 3.5 Radiation Passing through a Unit Cross Sectional Area Per Second

$$\therefore\ I = \rho.c. = \varepsilon_0 c E^2_{rms} \qquad (3.3.12)$$

Similarly, we can obtain

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

(9) $\vec{E} \times \vec{B}$ gives the direction of propagation of the electromagnetic wave.

Illustration 1 : Prove that the unit of $\frac{1}{\sqrt{\mu_0\varepsilon_0}}$ is that of velocity, using unit of μ_0 and ε_0.

Solution : The unit of $\mu_0 = \frac{N}{A^2}$, and the unit of $\varepsilon_0 = \frac{C^2}{Nm^2}$

$$\therefore \left[\frac{1}{\sqrt{\mu_0\varepsilon_0}}\right] = \frac{1}{\sqrt{\frac{N}{A^2}\ \frac{C^2}{Nm^2}}} = \frac{1}{\sqrt{\frac{A^2s^2}{A^2m^2}}} = ms^{-1}$$

Illustration 2 : A 1000 W bulb is kept at the centre of a spherical surface and is at a distance of 10 m from the surface. Calculate the force acting on the surface of the sphere by the electromagnetic waves, along with E_0, B_0, and intensity I. Take the working efficiency of the bulb to be 2.5 % and consider it as a point source. $\varepsilon_0 = 8.85 \times 10^{-12}$ SI and $c = 3.0 \times 10^8$ ms^{-1}. Also calculate the energy density on the surface.

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

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

$$\Delta U = 1000 \times \frac{2.5}{100}$$

$$\therefore\ \Delta U = 25\ Js^{-1}$$

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

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

$$\text{Intensity, } I = \frac{\text{The energy of the incident radiation per second}}{\text{Area}} = \frac{25}{1256} = 0.02\ \text{Wm}^{-2}$$

Now, $I = \varepsilon_0 c E_{rms}^2 = 0.02$

$$\therefore\ E_{rms} = \left[\frac{0.02}{8.85 \times 10^{-12} \times 3.0 \times 10^8}\right]^{\frac{1}{2}} = 2.74\ \text{Vm}^{-1}$$

$$\text{Now, } B_{rms} = \frac{E_{rms}}{c} = \frac{2.74}{3.0 \times 10^8} = 9.13 \times 10^{-9}\ \text{T}$$

$E_0 = \sqrt{2}\,E_{rms} = 3.87\ \text{Vm}^{-1}$ and $B_0 = \sqrt{2}\,B_{rms} = 1.29 \times 10^{-8}\ \text{T}$

The total energy incident on the surface = 25 J

$\therefore$ The momentum (Δp) imparted to the surface in one second (= force),

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

From $I = \rho c$, energy density

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

3.4 Electromagnetic Spectrum and Primary Facts of its Applications

After the Maxwell's theory of electromagnetic wave and its successful demonstration by Hertz, scientists started producing electromagnetic waves of different wavelengths.

It was established in the year 1906 that the X-rays discovered by Rontgen in 1895 were also electromagnetic waves. From that time onwards till now electromagnetic waves of wavelengths ranging from approximately 10^{-15} m to 10^8 m have been studied. Electromagnetic waves are continuously spreaded in this wavelength range. Out of the entire range of wavelengths, our eye is sensitive to only small region of wavelengths from about 4000 Å to about 7000 Å. We are blind as far as the other wavelengths are concerned (But this is actually the God given gift to us, otherwise the infrared radiation emitted by the surroundings during night, as well as other radiations of different wavelengths present during night could not allow us to slip, and there could not be any night for us). The sensitivity and the maximum response of the eyes of the various species is different to the electromagnetic spectrum. Many of the species are sensitive to the infrared or ultraviolet region along with visible region. Electromagnetic waves have been classified as per their wavelengths or frequencies, called electromagnetic spectrum (see figure 3.6). There are no sharp boundaries dividing the various sections of the electromagnetic spectrum.

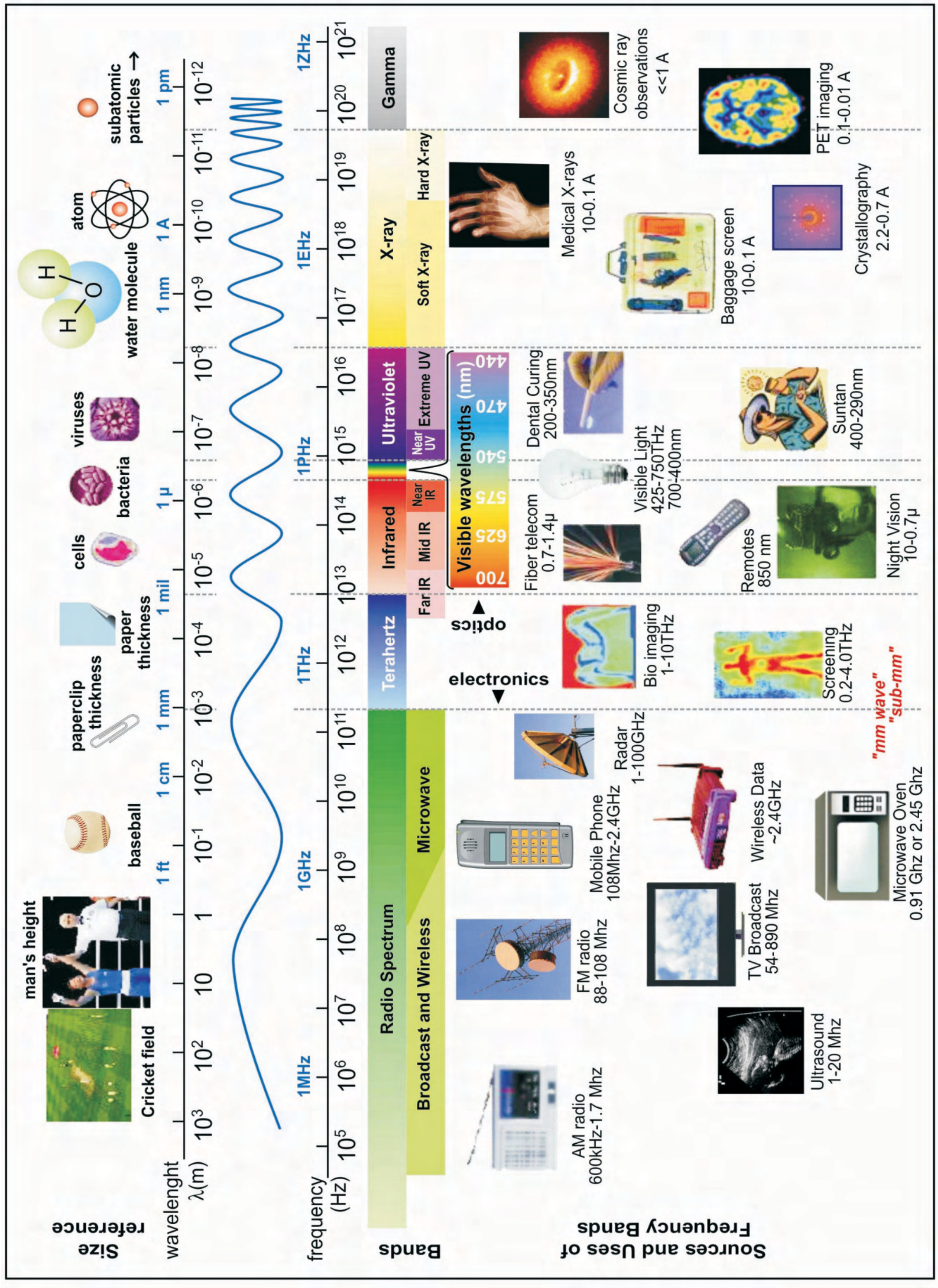


Figure 3.6 Electromagnetic Spectrum (Only For Information)

The brief discussion and applications of different regions of electromagnetic spectrum is as follows :

(1) Radio Waves : Radio waves are produced by the accelerated motion of charges in conducting wires. They are used in radio and television communication systems. The AM (amplitude modulated) band ranges from 530 kHz to 1710 kHz. Higher frequencies upto 54 MHz are used for short wave band. TV signals range from 54 MHz to 890 MHz. The FM (frequency modulated) radio band extends from 88 MHz to 108 MHz. Cellular phones use UHF (Ultra High Frequency) band for voice communication.

(2) Microwaves : Microwaves of about 0.3 GHz to 300 GHz range of frequency are produced by klystrons, magnetrons or Gunn diodes. They are suitable for radar systems used in aircraft, navigation and satellite communication. Radar also provides the basis for the speed guns used to time fast balls, tennis – serves, and intercepter vans by traffic police. Domestic microwave ovens operate at 0.915 GHz or 2.45 GHz to cook food or warm it up. When any food containing water molecules is placed in microwave oven, the water molecules rotate with this frequency. Thus, the microwave energy is transferred efficiently to the kinetic energy of water molecules, which raises the temperature of any food containing water.

(3) Infrared Waves : Infrared waves are produced by hot bodies and molecules. This band of waves lies between microwave band and the visible spectrum. The water molecules present in most materials readily absorb infrared waves (CO_2, NH_3 etc., also absorb infrared waves), due to which their thermal motion (thermal vibration) increases. This vibration increases the internal energy and hence the temperature of the substance increases. This is why the infrared waves are often called Heat Waves. Infrared lamps are used in physiotherapy.

The visible light from the sun is absorbed by the earth's surface, which in turn is re-radiated in terms of infrared radiations. This radiation is absorbed by green house gases like CO_2 and water vapour. This way, the infrared radiation plays an important role in maintaining the earth's warmth or average temperature through the greenhouse effect.

Infrared detectors are used in remote sensing satellites, for military purposes and in agriculture. The remote controller of TV, video players and hi–fi systems also use infrared (IR) LED (Light Emitting Diodes) for their operation.

(4) Visible Rays : Visible rays are a part of the radiation coming from the sun. These rays are also produced by flames, bulbs, incandesncent lamps etc. The visible region has frequency range from about 4×10^{14} Hz to about 7×10^{14} Hz or a wavelength range from about 700 nm to about 400 nm, respectively. Our eyes are sensitive to this range of wavelengths. Different animals are sensitive to different range of wavelengths. For example, snakes can also detect infrared rays, which help them to grab their prey from the infrared radiation being emitted by its body even during night.

For Information Only : The frequency (wavelength) range of visible spectrum is not well defined. The relative sensitivity of human eye to visible light of various wavelengths is shown in the given figure 3.7.

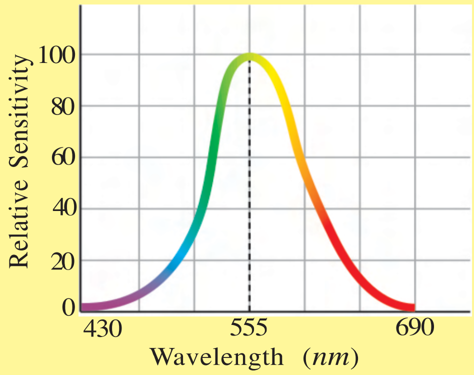


Figure 3.7

If we consider the limits as the wavelengths at which the sensitivity of eye drops to 1% of its maximum value, then these limits are about 430 nm and 690 nm. Human eye can detect electromagnetic waves some what beyond these limits if the intensity of light is high enough. The maximum sensation is produced at wavelength of about 555 nm, called yellow-green.

(5) Ultraviolet Rays : Ultraviolet (UV) radiation is produced by special types of lamps and very hot bodies. The sun is also an important source of UV radiation. Fortunately most of the UV radiation is absorbed in the ozone layer in the atmosphere which lies at an altitude of about 40-50 km from the surface of the Earth. UV radiation in large quantity is harmful to human body. UV exposure induces more production of melanin, causing tanning of the skin. Ordinary glass absorbs most of the UV radiation, so one can get less tanned or sun burn through the glass windows.

A large amount of UV radiation is produced by welding arcs. Hence, welders use face masks with dark glass windows or wear special glass goggles to protect their eyes. UV radiation has very short wavelength range from about 400 nm down to 0.6 nm. Thus, UV radiations can be focused into very narrow beams for high precision application such as LASIK (Laser-Assisted in Situ Keratomileusis) eye surgery. In some water purifiers UV lamps are used to kill germs.

The depletion of ozone from the UV protective ozone layers by the presence of CFCs (Chlorofluoro carbons) gas (such as freon) is a matter of international concern.

(6) X-rays : X-rays can be generated by bombarding a metal target by high energy electrons. The X-ray spectrum lies from about (10^{-8} m) down to about 10^{-4} nm (10^{-13} m) beyond the ultraviolet region in electromagnetic spectrum. X-rays are used in medical applications, to find the fracture in bones, as well as in a treatment of certain types of cancer. Because X-rays can damage or destroy living tissues and organisms, care must be taken to avoid unnecessary or over exposure.

(7) Gamma Rays : Gamma rays are produced during nuclear reactions and also emitted by radioactive nuclei. Gamma rays lie in the upper frequency range of the electromagnetic spectrum and have wavelength ranging from about 10^{-10} m to less than 10^{-14} m. Gamma rays are used in medicine to destroy cancer cells.

Table 3.1 summarises of different types of electromagnetic waves, their production and detection. It should be remembered that there is no sharp demarcation between any two regions.

TABLE 3.1 DIFFERENT TYPES OF ELECTROMAGNETIC WAVES

Type	Wavelength Range	Production	Detection
Radio	> 0.1 m	Rapid acceleration and decelerations of electrons in aerials.	Receiver's aerials (conducting wire)
Microwave	0.1 m to 1 mm	Klystron, magnetron valve, Gun diode.	Point contact diodes
Infra–red	1 mm to 700 nm	Vibration of atoms and molecules.	Thermopile, Bolometer, infrared photographic film
Visible Light	700 nm to 400 nm	Electrons in atoms emit light when they move from one energy level to a lower energy level.	The eye, photocells, photographic film, photo diode (LDR), light dependent resistor
Ultraviolet	400 nm to 1 nm	Inner shell electrons in atoms moving from one energy level to a lower level.	solar cell, Photocells, photographic film
X-rays	1 nm to 10^{-3} nm	X–ray tubes or inner shell electrons of atom	Photographic film, Geiger tubes, Ionization chamber,
Gamma rays	< 10^{-3} nm	Radioactive decay of the nucleus.	– do –

SUMMARY

1. The oscillating charges are responsible for the generation of periodically varying electric field in the space. Further, the oscillating charges generate varying electric current which in turn is responsible for the generation of periodically varying magnetic field. This way the electromagnetic waves are generated.
2. The frequency of generated electromagnetic waves is equal to the frequency of oscillation of the electric charges. In case of electromagnetic waves

   c (Velocity) $= \lambda$ (Wavelength) $\times f$ (Frequency)
3. In the region closer to the oscillating charges, the phase difference between $\vec{E}$ and $\vec{B}$ fields is $\frac{\pi}{2}$, and their magnitude quickly decreases as $\frac{1}{r^3}$ (where r = distance from the source). These components of the transmitted waves (or fields) are called inductive components.
4. At large distances from the source, $\vec{E}$ and $\vec{B}$ are in phase and the decrease in their magnitude is comparatively slower with distance, as per $\frac{1}{r}$. These components of electromagnetic radiation are called radiated components.
5. Electromagnetic waves are self sustaining oscillations of electric and magnetic fields in free space, or vacuum. No material medium is associated with vibrations of the electric and magnetic fields.
6. The velocity of electromagnetic waves in vacuum (free space) is

   $$c = \frac{1}{\sqrt{\mu_0 \varepsilon_0}} = 2.99792 \times 10^8 \text{ ms}^{-1}$$
7. The velocity of the electromagnetic waves in any medium is given by $v = \frac{1}{\sqrt{\mu\varepsilon}}$

   where μ = Permeability of the medium, and

   ε = Permittivity of the medium.
8. The velocity of light depends on electric and magnetic properties of the medium.
9. The refractive index of a medium is $n = \frac{c}{v} = \sqrt{\mu_r \varepsilon_r} = \sqrt{\mu_r K}$.
10. Electromagnetic waves exert pressure on a surface when they are incident on it, called radiation pressure.
11. If ΔU is the energy of electromagnetic waves incident on a surface of unit area per unit time normal to the direction of flow of energy, then assuming that the energy is completely absorbed, the momentum of the electromagnetic radiation transferred to the surface is $\Delta p = \frac{\Delta U}{c}$

    which also represents radiation pressure (P_S).
12. The electromagnetic energy per unit volume (energy density) in a region is given by

    $$\rho = \rho_E + \rho_B = \frac{1}{2}\varepsilon_0 E^2 + \frac{B^2}{2\mu_0} = \varepsilon_0 E^2_{rms}$$

13. The radiant energy passing through unit area normal to the direction of propagation in one second is called the intensity of radiation I.

14. The energy of the electromagnetic waves is equal to the kinetic energy of the charges oscillating between the two spheres.

EXERCISE

For the following statements choose the correct option from the given options :

1. The electromagnetic waves in the range of wavelengths from 3 mm to 100 cm are used for the purpose of satellite communication. The range of frequencies corresponding to this range of wavelengths is .... $[c = 3 \times 10^8 \ ms^{-1}]$

(A) 30 MHz to 10^4 MHz (B) 300 MHz to 10^5 MHz

(C) 3 MHz to 3×10^8 MHz (D) 3 MHz to 10^6 MHz

2. Astronomers have found that the electromagnetic waves of wavelength 21 cm are continuously reaching the Earth's surface. The frequency of this radiation is ....

$[c = 3 \times 10^8 \ m \ s^{-1}]$

(A) 1.43 GHz (B) 1.43 MHz (C) 1.43 kHz (D) 1.43 Hz

3. If v_g, v_x and v_m are the velocities of the γ-rays, X-rays and microwaves respectively in space, then

(A) $v_g > v_x > v_m$ (B) $v_g < v_x < v_m$ (C) $v_x > v_m > v_g$ (D) $v_g = v_x = v_m$

4. If μ_r be relative permeability and K be dielectric constant of a given medium, then the refractive index of the medium is n = ...

(A) $\sqrt{\mu_r K}$ (B) $\sqrt{\mu_0 \varepsilon_0}$ (C) $\frac{1}{\mu_r K}$ (D) $\sqrt{\frac{\mu_r}{K}}$

5. The maximum value of $\vec{E}$ in an electromagnetic wave is equal to 18 Vm^{-1}. Thus the maximum value of $\vec{B}$ is ....

(A) 3×10^{-6} T (B) 6×10^{-8} T (C) 9×10^{-9} T (D) 2×10^{-10} T

6. An electromagnetic wave passing through the space is given by equations : $E = E_0 \sin(\omega t - kx)$ and $B = B_0 \sin(\omega t - kx)$. Which of the following is true ?

(A) $E_0 B_0 = \omega k$ (B) $E_0 \omega = B_0 k$ (C) $E_0 k = B_0 \omega$ (D) $\frac{E_0}{B_0} = \frac{1}{\omega k}$

7. A plane electromagnetic wave is travelling along the X-direction. The electric field vector at an arbitrary point at a time is $\vec{E} = 6.3 \hat{j} \ Vm^{-1}$. The magnetic field at that point at that time is ....

(A) $2.1 \times 10^{-8} \hat{k}$ T (B) $-2.1 \times 10^{-8} \hat{k}$ T (C) $6.3 \hat{k}$ T (D) $-6.3 \hat{k}$ T

8. Two opposite charged particles oscillate about their mean equilibrium position in free space, with a frequency of 10^9 Hz. The wavelength of the corresponding electromagnetic wave produced is ....

(A) 0.3 m (B) 3×10^{17} m (C) 10^9 m (D) 3.3 m

9. The wavelengths 5890 Å and 5896 Å of sodium doublet correspond to .... region of the electromagnetic spectrum.

(A) infrared (B) visible light (C) ultraviolet (D) microwave

10. The frequency of an electromagnetic wave in free space is 2 MHz. When it passes through a region of relative permittivity $\varepsilon_r = 4.0$, then its wavelength .... and frequency ....

(A) becomes double, becomes half (B) becomes double, remains constant

(C) becomes half, becomes double (D) becomes half, remains constant

11. The rms value of electric field of the radiation coming from the Sun is 720 N/C. The average radiation density is .... Jm^{-3}.

(A) 81.35×10^{-12} (B) 3.3×10^{-3} (C) 4.58×10^{-6} (D) 6.37×10^{-9}

12. In the region closer to the oscillating charges, the phase difference between $\vec{E}$ and $\vec{B}$ fields is ...., and their magnitude quickly decreases as .... with distance r from the source.

(A) $0, r^{-1}$ (B) $\frac{\pi}{2}, r^{-3}$ (C) $\frac{\pi}{2}, r^{-1}$ (D) $0, r^{-3}$

13. At large distances from the source, $\vec{E}$ and $\vec{B}$ are in phase and the decrease in their magnitude is comparatively slower with distance r as per ...., and these components are called .... components.

(A) r^{-3}, inductive (B) r^{-1}, radiated (C) r^{-3}, radiated (D) r^{-1}, inductive

14. At room temperature, if the relative permittivity of water be 80, and the relative permeability be 0.0222, then the velocity of light in water is .... $m\ s^{-1}$.

(A) 3×10^8 (B) 2.5×10^8 (C) 2.25×10^8 (D) 3.5×10^8

15. If the electric field associated with a radiation of frequency 10 MHz is $E = 10 \sin(kx - \omega t) \frac{mV}{m}$, then its energy density is .... $J\ m^{-3}$. $[\varepsilon_0 = 8.85 \times 10^{-12}\ C^2 N^{-1} m^{-2}]$

(A) 4.425×10^{-16} (B) 6.26×10^{-14} (C) 8.85×10^{-16} (D) 8.85×10^{-14}

16. An electromagnetic wave coming from infinity, enters a medium from the vacuum. For this wave .... is independent of the medium. [will not change in the medium]

(A) ω (B) k (C) $\frac{\omega}{k}$ (D) λ

17. For a radiation of 6 GHz passing through air, the wave number (number of waves) per 1 m length is .... (1 GHz = 10^9 Hz).

(A) 3 (B) 5 (C) 20 (D) 30

18. In Hertz's experiment the .... of the electromagnetic waves is equal to the kinetic energy of the charges oscillating between the two spheres.

(A) frequency (B) energy (C) wavelength (D) velocity.

19. The intensity of a plane electromagnetic wave with $B_0 = 1.0 \times 10^{-4}$ T is .... Wm^{-2}

$[c = 3 \times 10^8\ m\ s^{-1}, \mu_0 = 4\pi \times 10^{-7}\ NA^{-2}]$

(A) 2.38×10^6 (B) 1.19×10^6 (C) 6×10^5 (D) 4.76×10^6

ANSWERS

1. (B)	**2.** (A)	**3.** (D)	**4.** (A)	**5.** (B)	**6.** (C)
7. (A)	**8.** (A)	**9.** (B)	**10.** (D)	**11.** (C)	**12.** (B)
13. (B)	**14.** (C)	**15.** (A)	**16.** (A)	**17.** (C)	**18.** (B)
19. (B)					

Answer the following questions in brief :

1. Who was the first scientist to demonstrate the existence of electromagnetic waves in the laboratory ?
2. Which term was missing in one of the equations relating electric and magnetic fields ?
3. What is the phase difference between $\vec{E}$ and $\vec{B}$ at large distance from the source ?
4. Who was the first scientist that generated the electromagnetic waves having wavelength ranging from 5 mm to 25 mm ?
5. Define intensity of radiations.
6. Which approximate wavelength ranges are generally not visible to human eye ?
7. Which type of waves are also called heat waves ?
8. Which type of rays are used for LASIK eye surgery ?
9. Which type of rays are produced during the nuclear reactions ?
10. Define the energy density of electromagnetic wave.

Answer the following questions :

1. Drawing the figure of Hertz's experiment, explain the generation of electromagnetic waves.
2. Drawing necessary figure, explain the inductive and radiated components of electromagnetic wave.
3. Explain any four characteristics of electromagnetic waves.
4. Give the information about the production of any two divisions of electromagnetic spectrum and their applications.

Solve the following examples :

1. The magnetic field of an electromagnetic plane wave travelling along the negative X-direction is given by $B_y = 2 \times 10^{-7} \sin (0.5 \times 10^3 x + 1.5 \times 10^{11} t)$ T. Calculate (*a*) the wavelength and frequency of the wave. (*b*) Write the equation of the electric field.

   [**Ans. :** $\lambda = 1.26$ cm, $f = 23.9$ GHz, $E_z = 60 \sin(0.5 \times 10^3 x + 1.5 \times 10^{11} t)$ Vm^{-1}]

2. 5 % of the total energy of a 100 W bulb is converted into visible light. Calculate the average intensity at a spherical surface which is at a distance of 1 m from the bulb. Consider the bulb to be a point source and let the medium be isotropic.

   [**Ans. :** 0.4 Wm^{-2}]

3. The maximum electric field at a distance of 10 m from an isotropic point source of light is 3.0 Vm^{-1}. Calculate (*a*) the maximum value of magnetic field, (*b*) average intensity of the light at that place, and (*c*) the power of the source.

[$c = 3 \times 10^8$ ms^{-1}, $\varepsilon_0 = 8.854 \times 10^{-12}$ $C^2 N^{-2} m^{-2}$]

[**Ans. :** $B_0 = 10^{-8}$ T, I = 1.195×10^{-2} Wm^{-2}, P = 15 W]

4. An observer is at 2 m from an isotropic point source of light emitting 40 W power. What are the rms values of the electric and magnetic fields due to the source at the position of the observer ? [$c = 3 \times 10^8$ m s^{-1}, $\varepsilon_0 = 8.854 \times 10^{-12}$ $C^2 N^{-1} m^{-2}$]

[**Ans. :** $E_{rms} = 17.3$ V m^{-1}, $B_{rms} = 5.77 \times 10^{-8}$ T]

5. A plane electromagnetic wave travelling along X-direction has electric field of amplitude 300 V m^{-1}, directed along the Y-axis. (*a*) What is the intensity of the wave ? (*b*) If the wave falls on a perfectly absorbing sheet of area 3.0 m^2, at what rate is the momentum delivered to the sheet and what is the radiation pressure exerted on the sheet ?

[**Take :** $\varepsilon_0 = 8.854 \times 10^{-12}$ $C^2 N^{-1} m^{-2}$, c = 3×10^8 ms^{-1}]

[**Ans. :** 119.529 W m^{-2}, 1.195×10^{-6} N, 3.98×10^{-7} P_a]

6. An electromagnetic wave of electric field $E = 10 \sin (\omega t - kx) \frac{N}{C}$ is incident normal to the cross-sectional area of a cylinder of 10 cm^2 and having length 100 cm, lying along X-axis. Find (*a*) the energy density, (*b*) energy contained in the cylinder, (*c*) the intensity of the wave, (*d*) momentum transferred to the cross-sectional area of the cylinder in 1 s, considering total absorption, (*e*) radiation pressure.

[**Take :** $\varepsilon_0 = 8.854 \times 10^{-12}$ $C^2 N^{-1} m^{-2}$, c = 3×10^8 ms^{-1}]

[**Ans. :** (*a*) 4.427×10^{-10} J m^{-3}, (*b*) 4.427×10^{-13} J, (*c*) 1.3278×10^{-1} Wm^{-2}
(*d*) 1.475×10^{-21} N (*e*) 1.475×10^{-18} N m^{-2}.]

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