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Unit- 8.Electromagnetic waves

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8. Electromagnetic Waves

Oersted experimentally predicted that the electric current produces a magnetic field. Faraday from his experiment on electromagnetic induction found that a changing maagnetic field produces an electric field.

At this time the clerk Maxwell state that the magnetic field is not only produced by electric current but also by a time varying electric field.

Maxwell formulated a set of equations involving electric and magnetic fields and their sources (the charge and current). These equations are Known as Maxwell's equations.

Maxwell's Equations

(1) $$\boxed{\oint_S \vec{E}\cdot\vec{dS} = \frac{q}{\epsilon_0}}$$

This equation is Gauss's Law in electrostatics. This gives the value of total electric flux in terms of the charge enclosed by the Surface s.

(2) $$\boxed{\oint_S \vec{B}\cdot\vec{dS} = 0}$$

This equation is Gauss's Law in magnetostatics. This law show that the number of magnetic field lines entering a closed surface is equal to number of magnetic field lines leaving it.

(3)

$$\boxed{\oint \vec{E}\cdot\vec{dl} = -\frac{d}{dt}\int_S \vec{B}\cdot\vec{dS}}$$

This equation is Faraday's Law of electromagnetic induction.

This law gives a relation between electric field and a changing magnetic flux. It shows that the line integral of electric field around any closed path (i.e. emf) is equal to the time rate of change of magnetic flux through the surface bounded by the closed path.

(4)

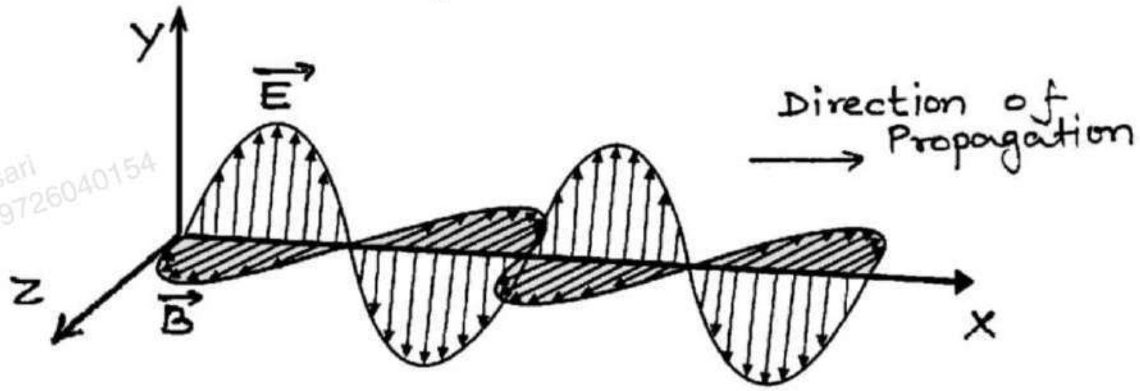
$$\boxed{\oint \vec{B}\cdot\vec{dl} = \mu_0 I + \mu_0 I_D} \qquad I_D = \epsilon_0 \int_S \frac{d\vec{E}}{dt}\cdot\vec{dS}$$

This equation is generalised form of Ampere's Circuital Law, modified by Maxwell and is known as Ampere'- Maxwell law.

This law shows that the line integral of the magnetic field around any closed path is related to the conduction current (I) and displacement current (I_D) through the path.

Electromagnetic Waves

According to Maxwell, the electromagnetic waves are those waves in which there are sinusoidal variation of electric and magnetic field vectors at right angles to each other as well as at right angles to the direction of wave propagation.



Both these fields ($\vec{E}$ and $\vec{B}$) vary with time and space and have the same frequency.

The electromagnetic waves can propagate through the space with the speed of light (3×10^8 m/s).

Maxwell also found that the electromagnetic waves should travel in free space (or vacuum) with a speed given by

$$\boxed{c = \frac{1}{\sqrt{\mu_0 \epsilon_0}}}$$

where μ_0 and ϵ_0 are permeability and permittivity of the free space respectively.

$$\mu_0 = 4\pi \times 10^{-7} \text{ Wb/Am}, \qquad \epsilon_0 = 8.85 \times 10^{-12} \text{ C}^2/\text{Nm}^2$$

$$\boxed{\text{velocity of EM waves in medium} = \frac{1}{\sqrt{\mu \epsilon}}}$$

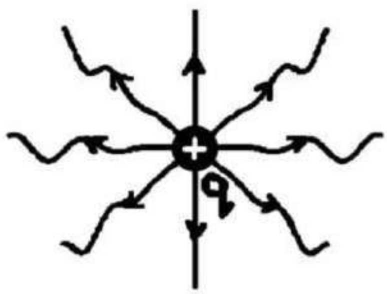
where μ and ϵ are the absolute permeability and permittivity of the medium.

Production of Electromagnetic Waves

If the charge is moving with a non-zero acceleration, both the magnetic field and electric field will change with space and time, it then produces electromagnetic waves. Hence an accelerated charge emits electromagnetic waves.

The L-C circuit is an oscillatory circuit where the charge is oscillating across the capacitor plates. An oscillating charge in L-C circuit has a non-zero acceleration hence it emitts electromagnetic waves, which have the same frequency as that of the oscillating charge.

In an atom an electron while orbiting around the nucleus in a stable orbit, does not emit electromagnetic waves. Electromagnetic waves are emitted only when it falls from higher energy orbit to lower energy orbit.



The Electric Field of an Oscillating Charge

Electromagnetic waves are also produced when fast moving electrons are suddenly stopped on the metal target of higher atomic number.

Properties of Electromagnetic Waves

(1) The electromagnetic waves are produced by the accelerated or oscillating charge.

(2) The EM waves do not require any material medium for propagation.

(3) These waves travel in free space with a speed 3×10^8 m/s (speed of light) and is given by the relation -

$$\boxed{C = \frac{1}{\sqrt{\mu_0 \epsilon_0}}}$$

(4) In electromagnetic waves the sinusoidal variation in both electric and magnetic field vectors ($\vec{E}$ & $\vec{B}$) occurs, simultaneously. As a result they attains the maximum and minimum values at the same place and at the same time.

The amplitudes of the electric and magnetic fields in free space are related by -

$$\boxed{C = \frac{E_0}{B_0}}$$

The equation of electric field and magnetic field varying sinusoidally with x and t can be given as -

$$\boxed{B_y = B_0 \sin(\omega t + Kx)} \qquad K = \frac{2\pi}{\lambda}$$

and

$$\boxed{E_z = E_0 \sin(\omega t + Kx)}$$

(5) The direction of variation of electric and magnetic field vectors are perpendicular to each other as well as perpendicular to the direction of propagation of waves. Therefore, electromagnetic waves are transverse in nature like light waves.

(6) The electromagnetic waves carry energy which is divided equally between electric field and magnetic field vectors.

In vacuum the average electric energy density (u_E) and average magnetic energy density (u_B) due to static electric field E and magnetic field B which do not vary with time are given by -

$$\boxed{u_E = \frac{1}{2}\epsilon_0 E^2} \quad \text{and} \quad \boxed{u_B = \frac{1}{2}\frac{B^2}{\mu_0}}$$

(7) The electric vector is responsible for the optical effect of an electromagnetic wave and is called the light vector.

(8) The electromagnetic waves being uncharged are not deflected by electric and magnetic fields.

(9) The velocity of EM wave in dielectric is less than c (3×10^8 m/s).

(10) <u>Poynting Vector ($\vec{S}$)</u>

The rate of flow of energy through unit area is called poynting vector, $\vec{S}$.

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

Also the intensity of plane electromagnetic wave I is average of the poynting vector.

$$\therefore \quad I = S_{av} = \frac{E_0 B_0}{2\mu_0}$$

or

$$\boxed{I = \frac{E_0^2}{2\mu_0 c} = c\,u_{av}} \quad \left[\because u_{av} = \frac{1}{2}\epsilon_0 E_0^2\right]$$

Momentum and Pressure associated with EM waves

An electromagnetic wave transports linear momentum as it travels through space.

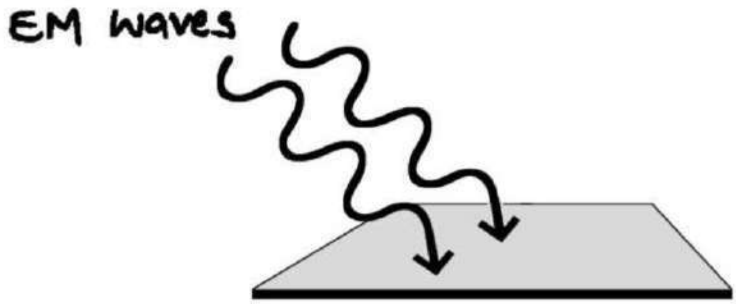
If an EM wave transfers a total energy U to a surface in time t, then total linear momentum delivered to the surface is

For completely absorbing surface

$$\boxed{\text{momentum } p = \frac{U}{c}}$$

If the wave is totally reflected, then

$$\boxed{\text{momentum } p = \frac{2U}{c}}$$



Also for totally absorbing surface radiation pressure is

$$\boxed{P = \frac{I}{c}}$$

and for completely reflecting surface

$$\boxed{P = \frac{2I}{c}}$$

Where I is the intensity of the wave.

[redacted]

Q. The magnetic field in a plane electromagnetic wave is given by $B_y = 2\times10^{-7}\sin(0.5\times10^{3}x + 1.5\times10^{11}t)$ T.
(a) What is the wavelength and frequency of the wave (b) Write an expression for the electric field

Sol: (a) Comparing the given equation with the equation of magnetic field varying sinusoidally with x and t as-

$$B_y = B_0 \sin\left(\frac{2\pi x}{\lambda} + \frac{2\pi t}{T}\right)$$

we get-

$$\frac{2\pi}{\lambda} = 0.5\times10^{3}$$

or $$\lambda = \frac{2\pi}{0.5\times10^{3}} = 1.26\times10^{-2}\,m$$

and $$\frac{2\pi}{T} = 1.5\times10^{11} \Rightarrow 2\pi\nu = 1.5\times10^{11}$$

so that $$\nu = \frac{1.5\times10^{11}}{2\pi} = 2.39\times10^{10}\,Hz$$

(b) $$B_0 = 2\times10^{-7}\,T$$

so that $$E_0 = cB_0 = 3\times10^{8}\times2\times10^{-7} = 60\,V/m$$

Here the electric field is varying along z-direction

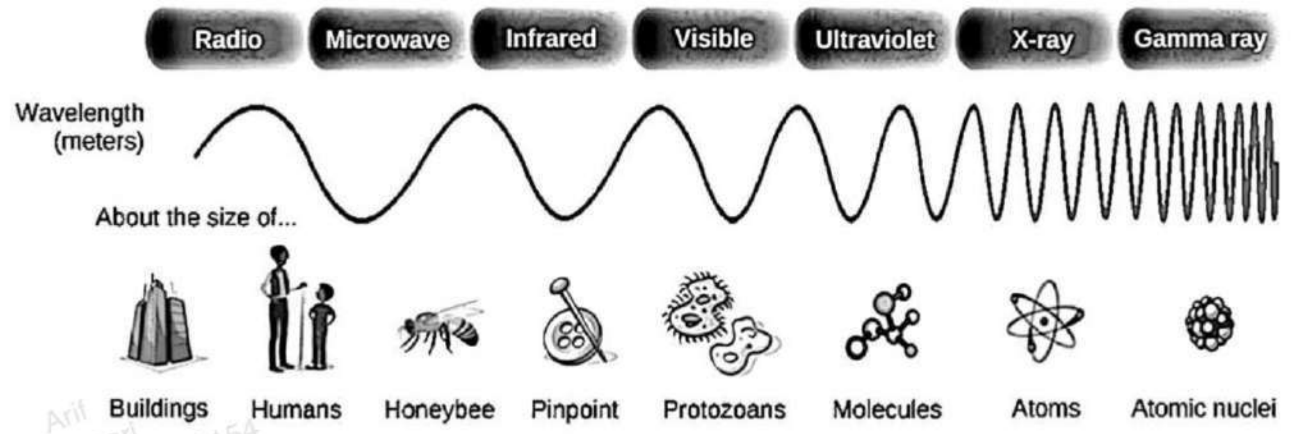
Thus- $$E_z = E_0\sin\left(\frac{2\pi x}{\lambda} + \frac{2\pi t}{T}\right)$$

or $$E_z = 60\sin(0.5\times10^{3}x + 1.5\times10^{11}t)\,V/m$$

Q. An electric bulb is emitting electromagnetic waves in all directions uniformly. Assuming electromagnetic emission to 50 W, Calculate at 3m from bulb
(a) Intensity (b) radiation pressure (c) Magnitude of electric and magnetic fields.

Answer: (a) $0.44\ W/m^2$ (b) $P = 1.47 \times 10^{-9}\ N/m^2$
(c) $E_0 = 18.2\ V/m$, $B_0 = 6.08 \times 10^{-8}\ T$

Main Parts of Electromagnetic Spectrum



(1) Radio Waves -

Frequency range

5×10^5 Hz to 10^9 Hz

These waves are produced by oscillating electric circuits having an inductor and capacitor.

Uses -

(1) The EM waves of frequency range from 530 KHz to 1710 KHz form amplitude modulated (AM) band. It is used in ground wave propagation.

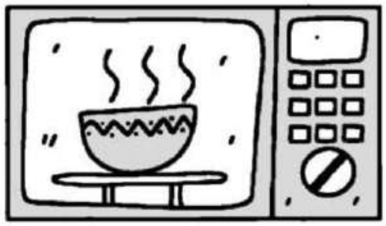
(2) The EM waves of frequency range 1710 KHz to 54 MHz are used for short wave bands. It is used in sky wave propagation.

(3) The electromagnetic waves of frequency range 54 MHz to 890 MHz are used in television waves.

(4) The electromagnetic waves of frequency range 88 MHz to 108 MHz form frequency modulated (FM) band. It is used for commercial FM radio.

(5) The EM waves of frequency range 300 MHz to 3000 MHz form ultra high frequency (UHF) band. It is used in cellular phone communication.

(2) Microwaves -



Frequency range

10^9 Hz to 3×10^{11} Hz

They are produced by special vacuum tubes called Klystrons, magnetrons and Gunn diodes etc.

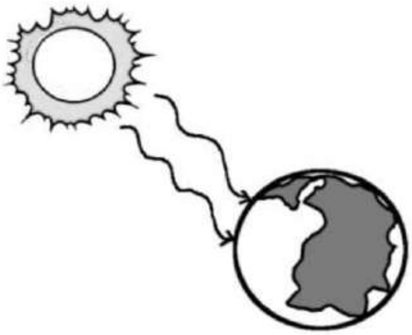
Uses -

(1) Microwaves are used in Radar system for air craft navigation.

(2) Microwave ovens are used for cooking purposes.

(3) A radar using microwave can help in detecting the speed of cricket ball, automobiles, aircrafts in motion.

(3) Infrared Waves -



Frequency range

3×10^{11} Hz to 4×10^{14} Hz

Infrared waves sometimes are called as heat waves because their absorption causes the heating effect in the bodies and surroundings.

Infrared waves are produced by hot bodies and molecules. These waves are not detected by human eye but snakes can detect them.

Use -

(1) in physical therapy i.e. to treat muscular strain.

(2) to provide electrical energy to satellite by using solar cells.

(3) in green houses to keep the plants warm and for producing dehydrated fruits.

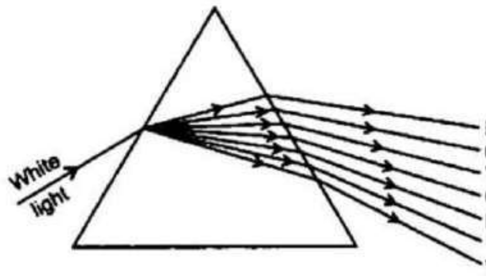
(4) For taking photographs during the condition of fog, smoke etc.

(5) in solar water heaters and Cookers.

(6) in checking the purity of chemicals and in the study of molecular structure by taking infra red absorption spectrum.

(7) in remote control.

(4) Visible Light -



Frequency range

4×10^{14} Hz to 8×10^{14} Hz

It is the narrow region of EM spectrum, which is detected by the human eye. It is produced due to atomic excitation.

Uses -

The visible light emitted or reflected from objects around us provides the information about the world surrounding us.

(5) Ultraviolet Rays -

Frequency range

8×10^{14} Hz to 5×10^{16} Hz

The ultraviolet rays are produced by sun, special lamps and very hot bodies.

Most of the ultraviolet rays coming from sun are absorbed by the ozone layer in the earth's atmosphere. The ultraviolet rays in large quantity produce harmful effect on human eyes.

Uses-

(1) for checking the mineral samples through the property of ultraviolet rays causing flourescence.

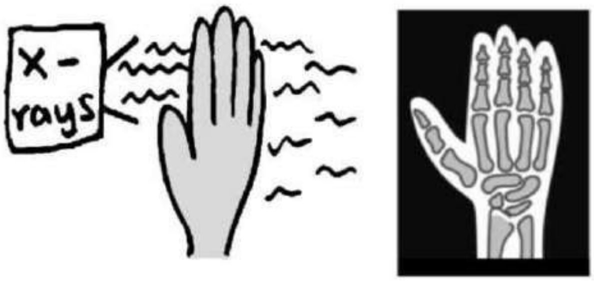
(2) in the study of molecular structure and arrangement of electrons in the external shell through ultraviolet absorption spectra.

(3) to distroy the bacteria and for sterilizing the surgical instruments.

(4) in the detection of forged documents, finger prints in forensic laboratory and in burglar alarm.

(6) X-rays -

Frequency range
10^{16} Hz to 3×10^{21} Hz



These are produced when high energy electrons are stopped suddenly on a metal of high atomic number. X-rays have high penetrating power.

Uses -

(1) In surgery for the detection of fractures, foreign bodies like bullets, diseased organs and stones in the human body.

(2) in Engineering for detecting faults, cracks and holes in final metal products.

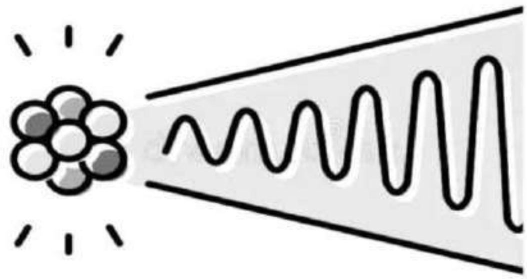
(3) in Radio therapy to cure untracable skin diseases and malignant growths.

(4) in detective departments for detection of gold, silver and explosives in the body of smugglers.

(5) in industry for the detection of defects in rubber tyers, gold and tennis balls etc.

(6) In scientific Research for the investigation of the crystal structure, arrangement of atoms, molecules in the complex substances.

(7) γ-rays -



Frequency range

3×10^{18} Hz to 3×10^{22} Hz

γ-rays have nuclear origin.

These rays are highly energetic and are produced by the nucleus of the radioactive substances.

Uses-

γ-rays are used

(1) in the treatment of cancer and tumours.

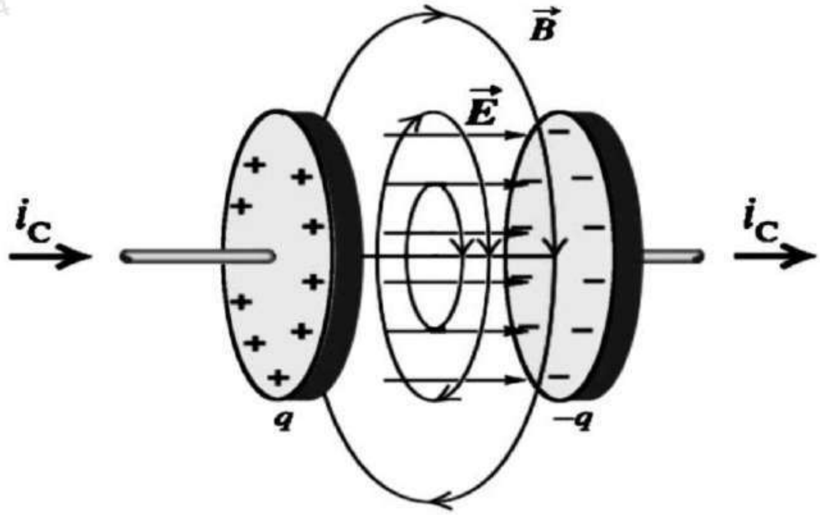
(2) to preserve the food stuff for a long time as the soft γ-rays can Kill micro-organisms easily.

(3) to produce nuclear reactions.

(4) to provide valuable information about the structure of atomic nucleus.

Q. CBSE 2011 A parallel plate capacitor is being charged by a time varying current. Explain briefly how Ampere's circuital law is generalised to incorporate the effect due to the displacement current.

Sol. While dealing with the charging of parallel plate capacitor with varying current, it was found that Ampere's circuital law is not logically consistent because $\oint_c \vec{B}\cdot\vec{dl}$ has not same value on the two sides of a plate of charged capacitor.



The inconsistency of Amper's circuital law was removed by Maxwell by predicting the presence of displacement current in the region between the plates of capacitor, when the charge on capacitor is changing with time.

Maxwell also predicted that the sum of conduction current and displacement current has the property of continuity.

The generalised form of Ampere's circuital law modified by Maxwell states that

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

displacement current $I_D = \epsilon_0 \dfrac{d\phi_E}{dt}$

Q. Name the Electromagnetic waves which
CBSE 2016
(a) maintain the earth's warmth and
(b) are used in aircraft navigation.

Sol. (a) Infrared rays maintain the earth's warmth
(b) Microwaves are used in aircraft navigation due to their short wavelength.

Q. Why is small ozone layer on top of the stratosphere crucial for human survival?
CBSE 2019

Sol. Because ozone layer traps most of ultraviolet rays coming from the sun and prevents harmful impact of ultraviolet rays.

Q. In an EM wave the oscillating electric field having a frequency of 3×10^{10} Hz and an amplitude of 30 V/m propagates in the positive x-direction.
CBSE 2008
(a) What is the wavelength of EM wave?
(b) Write down the expression to represent the corresponding magnetic field.

Sol. Given that – $\nu = 3 \times 10^{10}$ Hz, $E_0 = 30$ V/m

(a) $$\lambda = \frac{c}{\nu} = \frac{3 \times 10^8}{3 \times 10^{10}} = 10^{-2} \text{ m.}$$

(b) $$\because \quad c = \frac{E_0}{B_0} \quad \Rightarrow \quad B_0 = \frac{E_0}{c}$$

$$B_0 = \frac{30}{3 \times 10^8} = 1 \times 10^{-7} \text{ T}$$

Hence Magnetic field equation can be given as-

$$B = 10^{-7} \sin\left(\frac{2\pi x}{10^{-2}} + 2\pi \times 3 \times 10^{10} t\right)$$

$$B = 10^{-7} \sin\left(200\pi x + 6\pi \times 10^{10} t\right)$$

Q.1. *A parallel plate capacitor consists of two circular plates of radius R = 0.1 m. They are separated by a distance d = 0.5 mm. if electric field between the capacitor plates changes as*

$$\frac{dE}{dt}=5\times10^{13}\,\frac{V}{m\times s}$$

. Find displacement current between the plates.

Solution:

Area of plates $A=\pi r^2=3.14\times(0.1)^2\,m^2$

$$\frac{dE}{dt}=5\times10^{13}\,\frac{V}{m\times s}$$

$$I_d=\varepsilon_0 A\left[\frac{dE}{dt}\right]\quad\left\{\because\frac{d\phi_E}{dt}=A\frac{dE}{dt}\right\}$$

$$=8.85\times10^{-12}\times3.14\times(0.1)^2\times5\times10^{13}$$

$$I_d=13.9A$$

Q.2. What is the instantaneous displacement current in space between plates of parallel plate capacitor of capacitor $1\mu F$ which is charging at rate of $10^6 V/S$

Solution: As $I_d=\varepsilon_0\dfrac{d\phi_E}{dt}$

$$=\varepsilon_0 A\frac{d}{dt}(E)=\varepsilon_0 A\frac{d}{dt}\left(\frac{V}{d}\right)$$

$$=\frac{\varepsilon_0 A}{d}\frac{dV}{dt}=C\frac{dV}{dt};$$

$$I_d=10^{-6}\times10^{6}=1A$$

Q.3. Suppose that the electric field amplitude of an EM wave is $E_0 = 120 N/C$ and that its frequency $\nu = 50\,MH_Z$. Determine

(a) B_0, ω, λ and K

(b) Find expressions for E and B

Solution:

i) $$C = \frac{E_0}{B_0} \text{ we get}$$

$$B_0 = \frac{E_0}{C} = \frac{120}{3\times10^8} = 4\times10^{-7}T = 400nT$$

$$\omega = 2\pi\nu = 2\times\pi\times50\times10^6$$

ii) $$= 3.14\times10^8 \, rad/Sec$$

iii) $$c = \nu\lambda \Rightarrow \lambda = \frac{C}{\nu} = \frac{3\times10^8}{50\times10^6} = 6m$$

iv) $$K = \frac{2\pi}{\lambda} = \frac{2\pi}{6} = \frac{2\times3.14}{6} = 1.05m^{-1}$$

b) $$\vec{E} = E_0 \sin(kx - \omega t)$$

$$= 120\sin(1.05x - 3.14\times10^8 t)$$

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

$$= 400\times10^{-9}\sin(1.05x - 3.14\times10^8 t)$$

***Q.4.* Find the amplitude of the electric field in a parallel beam of light of intensity 10 watt/m^2.**

Solution:

Intensity of plane electromagnetic wave is

$$I = u_{av}c = \frac{1}{2}\epsilon_0 E_0^2 c$$

$$\text{or} \quad E_0 = \left(\frac{2I}{\epsilon_0 c}\right)^{1/2} = \left(\frac{2\times10}{8.85\times10^{-12}\times3\times10^{8}}\right)^{1/2}$$

$$= 86.8\ NC^{-1}$$

Q.5. In a plane E.M. wave the electric field oscillates sinusoidally at a frequency 3×10^{10} Hz and amplitude 50 Vm^{-1}.

(a) What is the wavelength of the wave

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

Solution:

Frequency $\nu = 3\times10^{10}\,Hz,\ E_0 = 50\,Vm^{-1}$

(a)Wavelength,

$$\lambda = \frac{c}{\nu} = \frac{3\times10^{8}}{3\times10^{10}} = 10^{-2}\,m = 1\,cm$$

(b) Amplitude of oscillating magnetic field,

$$B_0 = \frac{E_0}{c} = \frac{50}{3\times10^{8}} = 1.67\times10^{-7}\,T$$