Course Title

Course Code PHS 102 / Department: PHYSICS

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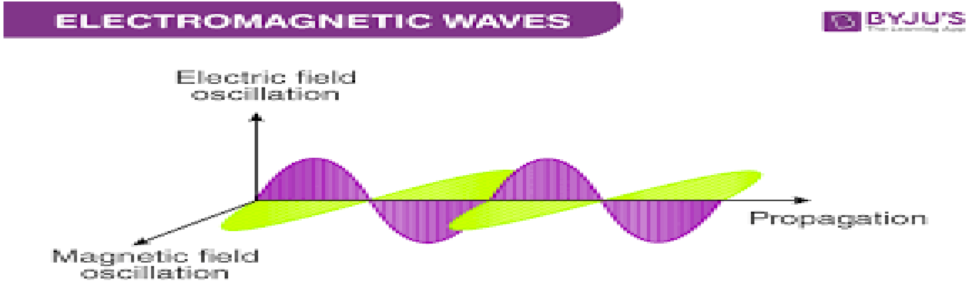
ELECTROMAGNETIC WAVES

Electromagnetic waves or EM **waves** are **waves** that are created as a result of vibrations between an electric field and a magnetic field. In other words, EM **waves** are composed of oscillating magnetic and electric fields



These are waves composed of undulating electrical fields and magnetic fields. The different kind of EM waves such as light and radio waves form the electromagnetic spectrum.

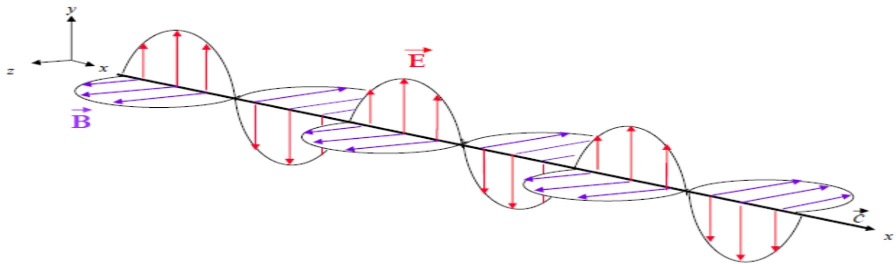
Note that all EM waves have the same speed in a vaccum (expressed by the letter c) and is equal to about 3 x 10^8m/s.

Maxwell's theory is a mathematical formulation that relates electric and magnetic phenomena. His theory, among other things predicted that electric and magnetic fields can travel through space as waves. He predicted that

(i) a changing electric field produces a magnetic field

(ii) an accelerating charges will radiate EM waves and that

(iii) the electric and magnetic fields in the wave are fluctuating. The figure below shows an EM waves in picture.



Properties of EM Radiation

Note that the Electric field due to a point charge q can be determined by applying Coulomb's law given as $\nabla . E = {}^{\rho}/_{\varepsilon_0}$ where $\rho = {}^{q}/_{v}$ is the electric charge density (charge per unit volume).

Electric fields originate on positive charges and terminate on negative charges while magnetic field lines always from closed loops (i.e they do not begin or end anywhere). This means that there are no magnetic monopoles.

This is given by Maxwells equation as $\nabla . E = O$ (the "zero" implying that there are no magnetic monopoles).

A varying magnetic field B induces an E.M.F and hence electric field (this is Faraday's law and is now re-expressed in Maxwell's form as $\nabla \mathrm{X}\, E = \frac{-\partial B}{\partial t}$.

Also magnetic fields are generated by moving charges (or current). This is Ampere's law and is re-expressed in Maxwell's form as $\nabla \mathrm{X}\, B = \mu_0 J$.

EM waves (i.e radiation) propagate at a velocity given by $c = \frac{1}{\sqrt{\mu_0 \varepsilon_0}}$ = 2.99792 x 10^8m/s

EM waves are emitted from oscillating electric charges i.e An oscillating electric charges produces an Electric field that varies in time, which produces a B-field that also varies in time, which produces a new E-field that varies in time and so on.

EM waves also behave like particles, planck called a packet of electromagnetic radiation a photon in the early 1900s.

EM waves are transverse waves, since the electric and magnetic fields are perpendicular to the direction of propagation of the wave and to each other.

EM waves carry both energy and momentum (despite have no mass) hence the energy is proportional to frequency and inversely proportional to wavelength. The energy is given by $E = hv = \frac{hc}{\lambda}$ where v is the frequency of an EM waves

In summary, these are properties of EM waves

EM waves all travel speed of light c where $c^2 = \frac{1}{\mu_0 \varepsilon_0}$

The E and B fields are perpendicular to each other

The E and B fields are in phase (both reach a maximum and minimum at the same time).

The E and B fields are perpendicular to the direction of travel (transverse waves) i.e. perpendicular E and B propagate through space in direction of E X B.

The magnitude of E and B in empty space are related by the expression $\frac{E}{B} = C$

Example: An EM wave in a vacuum has an electric field amplitude of 220v/m. calculate the amplitude of the corresponding magnetic field.

Solution: Note that the ratio of the maximum magnitude of the E-field to the maximum magnitude of the B-field of an EM wave is

$$\frac{Emax}{Bmax} = C \;\therefore Bmax = \frac{Emax}{C} = \frac{220v/m}{3x10^{8}m/s} = 7.33\text{ X}10^{-7}T = 733nT$$

Electromagnetic waves are produced by________

ANSWER: An accelerated charge

The direction in which electromagnetic waves propagate is the same as that of

ANSWER: $\vec{E} \times \vec{B}$

ELECTROMAGNETIC SPECTRUM

The EM spectrum is defined to be the intensity of an EM wave as a function of wave length, frequency or energy. EM waves can be generated in different frequency bands. The continuous EM spectrum is split into different regimes. Below is the list of EM spectrum from shortest to longest wavelength with distinct wavelength dividng lines.

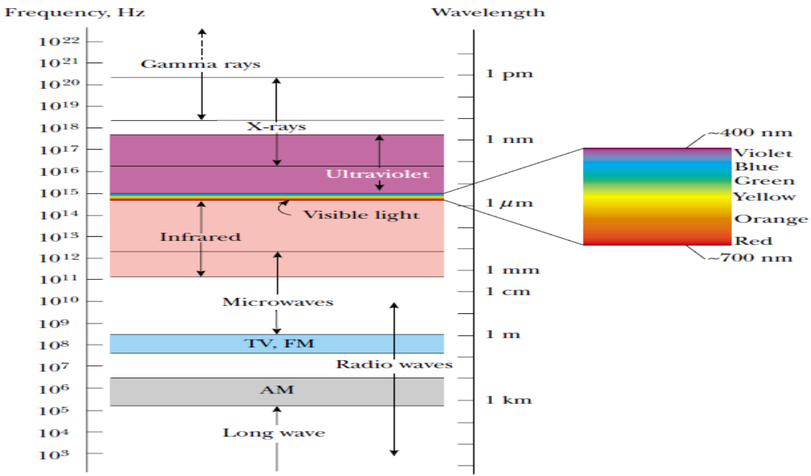
Gamma rays → X-rays → UV → Visible light → Intra Red → Micro waves → Radio waves.

Radio waves: wavelengths range from more than 10^4 m to about 0.1m. They are the result of charges accelerating through conducting wires. They are generated by such electronic devices such as LC oscillators and are used in radio and television communication systems.

Microwaves: wavelengths range from 0.3m to 10^{-4} m and are also generated by electronic devices. They are used in radar system and for studying the atomic and molecular properties of matter.

Infra Red waves: wavelengths ranging from 10^{-3} m – 7 x 10^{-7} m. They are used in physical therapy, IR photography and vibrational spectroscopy.

Visible light: wavelengths range from 4 x 10^{-7} m – 7 x 10^{-7} m. The sensitivity of the human eye is a function of wavelength, being maximum at a wavelength of about 5.5 x 10^{-7} m.



(Note: visible light ranges than from 400mm – 700mm (4000Å - 7000Å)

Note: 1Å = 10^{-10}m.

Some spectral regions are sub-divided into smaller bands. In case of visible spectrum between 500 – 570nm which is also the wavelengths where the sun emits the peak of its intensity in the EM spectrum (natural selection at work!).

Example: The eye is most sensitive to light of wavelength 5.5 x $10^{-7}{}_{m}$ which is in the G-Y region of the visible spectrum. Calculate the frequency of this light?

Solution: $v = \frac{C}{\lambda} = \frac{3\times10^{8}m/s}{5.5\times10^{-7}m} = 5.45 \times 10^{14}Hz$

The Doppler Effect for EM radiation

The spectrum of an object will be <u>blue shifted</u> if it is approaching the observer

The spectrum of an object will be <u>red shifted</u> if it is receding from an observer.

The wavelength shift in a spectral line is given by $\frac{\Delta\lambda}{\lambda_0} = \frac{Vr}{C} \therefore \frac{\Delta\lambda c}{\lambda_0} = \frac{0.37Å}{6562.85Å}\left(3 \times \frac{10^8 m}{s}\right)$

$$= (-5.638 \times 10^{-5})\left(3 \times \frac{10^8 m}{s}\right)$$

= -1.69 X 10^4m/s = -16.9 km/s.

i.e Polaris is moving towards as (-ve sign and the line was blue shifted at 16.9km/s).

ENERGY CARRIED BY EM WAVES

EM waves carry energy, and as they propagate through space, they can transfer energy to objects placed in their path.

The rate of flow of energy in an EM wave is described by a vector S called the Poynting vector defined by the expression $S \equiv \frac{E \times B}{\mu_0}$. The magnitude of S represents power per unit area (i.e the rate at which energy flows through a unit surface area) perpendicular to the direction of propagation.

For a plane EM wave where $|E \times B| = EB \;\therefore S = \frac{EB}{\mu_0},\ from\ B = \frac{E}{C}$, we can also express S as $S = \frac{E^2}{\mu_0 C} = \frac{c}{\mu_0} B^2$.

The average value of S (the intensity of the wave) is given by

$$I = S_{av} = \frac{E_{max}\, B_{max}}{2\mu_0} = \frac{E^2{}_{max}}{2\mu_0 c} = \frac{cB^2{}_{max}}{2\mu_0}$$

$$I = cU_{av}\,, \qquad where\ U_{av} = \frac{1}{2}\mathcal{E}_0 E^2{}_{max} = \frac{B^2{}_{max}}{2\mu_0}$$

The intensity of an EM wave equals the average energy density multiplied by the speed of light.

Note: The instantaneous energy density U_E associated with an Electric field is given by $U_E = ½\, E_0\, E^2$ and that associated with magnetic field $U_B = \frac{B^2}{2\mu_0}$.

$$U_B = \frac{\left(\frac{E}{C}\right)^2}{2\mu_0} = \frac{\varepsilon_0 \mu_0 E^2}{2\mu_0} = \frac{1}{2}\varepsilon_0 E^2 \;\therefore\; U_B = U_E = \frac{1}{2}\varepsilon_0 E^2 = {B^2}/{2\mu_0}$$

.: The energy density U of an EM wave is given by

$$E = \frac{1}{2}\varepsilon_0 E^2 + \frac{1}{2}\mu_0 B^2 = \varepsilon_0 E^2 = \frac{1}{\mu_0}B^2$$

Example: The Electric field in an EM wave is described by

$$E_y = 100 sin\,(1.00 \times 10^7 x - wt)$$

Find the amplitude of the corresponding magnetic field oscillations

The wavelengths ʎ and (c) the frequency f

Solution:

Using $B = \frac{E}{C} .. B = \frac{100\, v/m}{3 \times 10^8 m/s} = 3.33 \times 10^{-7} T = 0.333 \mu T$

$$⅄ = \frac{2\pi}{K} = \frac{2\pi}{1 \times 10^7 m^{-7}} = 0.628 \mu m$$

$$f = \frac{C}{\Lambda} = \frac{3 \times 10^8 m/s}{628 \times 10^{-7} m} = 4.77 \times 10^{14} Hz$$

Example: How much energy per cubic metre is contained in sunlight, if the intensity of the sunlight at the Earth surface under a fairly clear sky is 1000w/m^2?

Solution: $S = I = \frac{U}{At} = \frac{Uc}{V} = UC = IV \;\therefore \frac{U}{V} = \frac{I}{C} = \frac{1000 w/m^2}{3 \times 10^8 m/s} = 3.33 \mu J/m^3$