Electromagnetic wave and its mass

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Abstract: In the present paper, I have shown that the electromagnetic wave is always associated with mass along with its electromagnetic field. The mass and energy that is carried out by electromagnetic wave is depends upon the medium through which it passes. Existence of mass of EM wave along with its electric and magnetic field gives the wave-particle nature of electromagnetic wave at same time.

Keywords: Electromagnetic waves, photon mass, Maxwell's equation, mass-energy relation, wave-particle duality.

INTRODUCTION:

Any accelerating charge particle produces electromagnetic wave. Electromagnetic (EM) wave consists of electric and magnetic field which travels perpendicular to each other and perpendicular to its direction of propagation. James Maxwell have derived a wave form of the electric field and magnetic field equations [1,2]. The speed of electromagnetic wave calculated from Maxwell's equation shows that these waves are travelling at the speed of light in vacuum i.e. at a speed (c) of 2.9979 X 10^8 m/s, from this Maxwell concluded that light itself is an EM wave [1,2,3]. A. Einstein Shows that a light is emitted as well as absorbed in discrete quanta of energy ($h\nu$) called photon [4]. It has shown that the photon is the particle of electromagnetic field [5]. According to wave-particle duality principle, electromagnetic wave exhibits both wave and particle properties at the same time [3,6].

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M. Newstead et al[7] have concluded that the EM wave has zero mass at speed c, and when collides with matter its mass is given by $m = \frac{h\nu}{c^2}$. But studies [8-11] have shown that photon always carries mass equivalent to its energy. Since photon is an EM wave, the EM wave has to carry mass equivalent to its energy. In present work, I have shown that EM wave is always associated with mass equivalent to its energy along with Electric and magnetic field and the amplitude of electromagnetic field is depends upon energy and mass of EM wave.

1. MASS OF ELECTROMAGNETIC WAVE:

James Maxwell's equations are the foundation of classical electrodynamics, classical optics and electrical circuit. Maxwell's equations describe how electric and magnetic fields are generated and altered by each other and by charges and currents [2].

Let us see the Maxwell's equations [1-3] by considering electromagnetic wave as a monochromatic wave in empty space, with no currents or charges present.

$$\vec{\nabla}.\vec{E} = 0 \quad (1)$$

$$\vec{\nabla}.\vec{B} = 0 \quad (2)$$

$$\vec{\nabla} \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \quad (3)$$

$$\vec{\nabla} \times \vec{B} = \mu_0 \varepsilon_0 \frac{\partial \vec{E}}{\partial t} \quad (4)$$

Where, $\vec{E}$ is the electric field, $\vec{B}$ is the magnetic field, μ_0 is the permittivity, and ε_0 is the permeability of the free space.

According to Maxwell's equations, a spatially varying electric field is always associated with a magnetic field that changes over time and given by following equations [11]

$$E = E_m \sin(\kappa x - \omega t) \quad (5)$$

$$B = B_m \sin(\kappa x - \omega t) \quad (6)$$

Where, $\kappa = 2\pi / \lambda$ is the wave number,

$\omega = 2\pi\nu$ is the angular frequency,

E_m and B_m are the amplitudes of the electric and magnetic field.

The energy and momentum carried by photon are related to frequency (ν) and wavelength (λ) i.e.

$$\text{Energy } (E) = h\nu = \hbar\omega \quad (7)$$

$$\text{Momentum } (p) = \frac{h}{\lambda} = \hbar\kappa \quad (8)$$

But, the energy and momentum of photon [8-11] in terms of its mass is given by

$$E = mc^2 \quad (9)$$

$$p = mc \quad (10)$$

From equations (7) to (10), we can write,

$$\omega = \frac{mc^2}{\hbar}$$

$$\kappa = \frac{mc}{\hbar}$$

Therefore equation (5) and (6) of electromagnetic field in terms of mass can be written as follows,

$$E = E_m \sin\left[\frac{mc}{\hbar}(x - ct)\right]$$

$$B = B_m \sin\left[\frac{mc}{\hbar}(x - ct)\right]$$

From the Maxwell's third equation (3) we can write the x components of the equation as,

$$\frac{\partial E}{\partial x} = -\frac{\partial B}{\partial t}$$

By putting the values of E & B in above equation and by differentiating we get,

$$\frac{mc}{\hbar} E_m \cos\left[\frac{mc}{\hbar}(x - ct)\right] = -\left(-\frac{mc^2}{\hbar} B_m \cos\left[\frac{mc}{\hbar}(x - ct)\right]\right)$$

$$E_m \cos\left[\frac{mc}{\hbar}(x - ct)\right] = cB_m \cos\left[\frac{mc}{\hbar}(x - ct)\right]$$

Therefore,

$$c = \frac{E_m}{B_m} \quad (11)$$

The above equation gives the relation between speed of light or photon and the amplitude of electric and magnetic component of EM wave.

Also, $$c = \frac{\omega}{\kappa} = \frac{2\pi\nu}{2\pi / \lambda} = \frac{\nu}{\lambda}$$

Therefore, $$c = \frac{\omega}{\kappa} = \frac{E_m}{B_m}$$

The speed of light or photon is also related to the permittivity and permeability of the medium. Speed of photon when travelling in vacuum is given by following equation [1,2,11]

$$c = \frac{1}{\sqrt{\mu_0 \varepsilon_0}} \quad (12)$$

By putting the values of speed of photon (c), from equations (11) and (12), into the equation (9) and (10), we can write the equation of energy and momentum carried by electromagnetic wave of mass (m) is,

$$E = mc^2 = m\frac{1}{\mu_0\varepsilon_0} = m\frac{E_m^2}{B_m^2} \quad (13)$$

$$p = mc = m\frac{1}{\sqrt{\mu_0\varepsilon_0}} = m\frac{E_m}{B_m} \quad (14)$$

Above equation gives the energy and momentum of electromagnetic wave in terms of its mass and its electric and magnetic field amplitudes.

Therefore from energy and momentum relation, the mass of EM wave can be written as,

$$m = E\mu_0\varepsilon_0 = E\left(\frac{B_m^2}{E_m^2}\right)$$

$$m = p\sqrt{\mu_0\varepsilon_0} = p\left(\frac{B_m}{E_m}\right)$$

From above equations it is shown that energy and momentum of EM wave are always associated with its mass along with electric and magnetic component of the electromagnetic wave. Also mass and energy of EM wave depends upon the medium through which EM wave travels.

2. CONCLUSION:

Here I have shown that the electromagnetic wave always carry mass depending upon its energy along with its electric and magnetic field component. Because the speed of light is depends upon the medium, the mass and energy of light are also depends upon the medium through which is passes. This theory explains how EM wave exhibits wave as well as particle nature at same time. Electromagnetic field gives wave nature and mass gives particle nature of EM wave.

3. REFERENCES:

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