ELECTROMAGNETIC WAVES

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Sources of electromagnetic waves

- Electromagnetic waves are created when charges accelerate. Stationary charges or charges moving at a steady, constant speed do not produce these waves. Stationary charges create only an electrostatic field, and steady currents generate magnetic fields that do not change with time.

- According to Maxwell's theory, when charges undergo acceleration, they emit electromagnetic waves. While a rigorous proof of this concept is complex, we can grasp it qualitatively. Imagine a charge that oscillates back and forth with a certain frequency. This oscillation involves changes in speed, which means the charge is accelerating. As it oscillates, it generates an oscillating electric field in the surrounding space.

- This electric field, in turn, creates an oscillating magnetic field, and the cycle continues. The oscillating magnetic field becomes a source for another oscillating electric field, and this process repeats as the waves travel through space.

- The frequency of these electromagnetic waves matches the frequency of the charge's oscillation. In simple terms, if the charge wiggles back and forth rapidly, the resulting waves have a high frequency.

- Importantly, the energy carried by these waves originates from the energy of the source, which is the accelerating charge. As the charge accelerates, it loses some of its energy, which is then transferred to the propagating electromagnetic waves.

- In essence, electromagnetic waves are created when charges undergo acceleration and set up a cycle of oscillating electric and magnetic fields that regenerate each other. The frequency of these waves matches the frequency of the charge's oscillation, and the energy of the waves comes from the energy of the accelerating charge.

Nature of electromagnetic wave

Maxwell's equations demonstrate that the electric and magnetic fields in an electromagnetic wave are at right angles to each other and to the wave's direction of movement. This conclusion aligns with our previous discussion regarding the displacement current. To illustrate this, let's examine the electric field within the plates of a capacitor, which is oriented perpendicular to the plates. As a result of the displacement current, it gives rise to a magnetic field that encircles a circle parallel to the capacitor plates. This means that the magnetic field (B) and the electric field (E) are perpendicular in this scenario.

This alignment holds true as a general principle. In the diagram, we present a typical example of a flat electromagnetic wave advancing along the z-direction (the fields are depicted as functions of the z-coordinate at a specific time, t). The electric field (E_x) is positioned along the x-axis and fluctuates in a sinusoidal manner with respect to z, at a particular moment in time.

The magnetic field, denoted as B_y, is oriented along the y-axis and also exhibits sinusoidal variation with respect to z. In this case, the electric field E_x and the magnetic field B_y are at right angles to each other, as well as to the propagation direction along the z-axis.

We can express these fields, E_x and B_y, in the following manner

$E_x = E_0 \sin (kz - \omega t)$............ Equation 7(a)

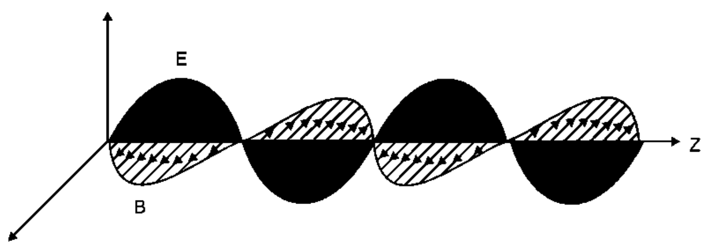
$B_y = B_0 \sin (kz - \omega t)$............ Equation 7(b)

In these equations, k is connected to the wavelength λ of the wave through the standard relationship:

$K = \frac{2\pi}{\lambda}$ ..... (8)

The symbol ω represents the angular frequency, and k signifies the magnitude of the wave vector, also known as the propagation vector. The direction of k illustrates the wave's direction of propagation. The wave's speed of propagation is given by (ω/k).

By analyzing the expressions for E_x and B_y provided in equations (a) and (b), and utilizing Maxwell's equations, we can derive that:



$\omega = cK, where, c = 1/\sqrt{\mu_0 \varepsilon_0}$ ......Eq (9) (a)

The relationship ω = cK is a fundamental equation for describing waves. This equation is frequently expressed in terms of frequency.

ν (=ω/ 2π) and wavelength. λ (= 2π / k) as

$$2\pi v = c\left(\frac{2\pi}{\lambda}\right)$$

$\nu\lambda = c$ ......Eq. 9(b)

Maxwell's equations reveal that the magnitudes of the electric and magnetic fields in electromagnetic waves are connected, expressed as $B_0 = E_0 / c$. Electromagnetic waves represent self-sustaining oscillations of electric and magnetic fields occurring in free space, such as a vacuum. They differ from other types of waves we have explored thus far because they don't require a material medium for their vibrations. Sound waves in air, for instance, consist of compressions and rarefactions and are longitudinal waves. Water waves, on the other hand, are transverse waves that travel horizontally and radially outward. Transverse elastic waves, or sound waves, can also travel through rigid solids.

In the 19th century, scientists commonly adhered to a mechanical model that involved a hypothetical substance called ether permeating all space and matter, which was believed to respond to electric and magnetic fields much like any elastic medium would. It was thought that this ether was the medium through which electromagnetic waves propagated. However, it was conclusively demonstrated through the Michelson-Morley experiment in 1887 that ether did not exist. We now understand that electromagnetic waves can sustain themselves in a vacuum without the need for any physical medium.

But what if a material medium is present? Electromagnetic waves, like light, can indeed travel through substances such as glass. We previously discussed how the total electric and magnetic fields within a medium are described in terms of permittivity (ε) and magnetic permeability (μ), which represent the factors by which the total fields deviate from the external fields. These values replace ε0 and μ0 in Maxwell's equations when describing electric and magnetic fields in a material medium. As a result, the speed of light within this medium becomes defined by:

$$\upsilon = \frac{1}{\sqrt{\mu\varepsilon}} \qquad \text{...... (10)}$$

The velocity of light is dependent on the electric and magnetic properties of the medium through which it propagates. In the case of electromagnetic waves traveling through free space or a vacuum, the velocity of light represents a fundamental constant. Experiments involving electromagnetic waves of different wavelengths have consistently shown that this velocity remains the same, regardless of the wavelength, with variations of only a few meters per second observed. The established constancy of the velocity of electromagnetic waves in a vacuum is well-supported by experimental evidence, and the precise value of this velocity is widely known. In fact, it is so well-established that it is used as a standard reference for defining length.

Hertz made significant contributions by not only confirming the existence of electromagnetic waves but also by demonstrating their ability to undergo phenomena such as diffraction, refraction, and polarization. This work led to the definitive conclusion that electromagnetic radiation behaves as waves. Additionally, Hertz generated stationary electromagnetic waves and determined their wavelength by measuring the distance between consecutive nodes. With the frequency of the wave already known (equal to the oscillator's frequency), he calculated the wave's speed using the formula $v = \nu\lambda$ and found that the waves traveled at the same speed as light.

Absolutely, electromagnetic waves indeed carry both energy and momentum, similar to other types of waves. In a region of free space where there's an electric field E, an associated energy density is present, given by ($\varepsilon_0 E^2/2$). Similarly, a magnetic field B is associated with magnetic energy density ($B^2/2\mu_0$). Since electromagnetic waves consist of both electric and magnetic fields, they possess a non-zero energy density.

Now, let's consider a plane that is perpendicular to the direction of propagation of the electromagnetic wave. If there are electric charges on this plane, these charges will experience a force and be set into motion by the electric and magnetic fields of the electromagnetic wave. Consequently, these charges gain energy and momentum from the waves. This scenario highlights that electromagnetic waves, like other waves, transport both energy and momentum.

Because electromagnetic waves carry momentum, they exert a pressure known as radiation pressure. For an absorbing surface, the magnitude of the total momentum delivered to the surface over a time interval t is given by:

$$P = \frac{U}{c} \qquad \text{...... (11)}$$

This relationship demonstrates that light, which is an electromagnetic wave, delivers energy from the sun to the Earth, playing a vital role in making life possible on our planet.

Example.

Think of a flat electromagnetic wave moving through empty space. At a certain place and time, the strength of the electric field (E) is 6 volts per meter (V/m). We want to know what the strength of the magnetic field (B) is at that very spot.

Solution.

Eq the magnitude of B is

$$B = \frac{E}{c}$$

$$= \frac{6.3 V/m}{3\times10^{8} m/s} = 2.1\times10^{-8} T$$

To find the direction, we note that E is along y-direction and the wave propagate along x-axis. Therefore, B should be in a direction perpendicular to both x- and y-axes. Using vector algebra,

E × B should be along x-direction. Since, $(+j) \times (+K) = \hat{i}$, B is along the z-direction

Thus, B = 2.1×10^{-8} kT