

CHAPTER 24

Electromagnetic Waves

24.1

DISPLACEMENT CURRENT AND THE GENERALIZED AMPERE'S LAW

Displacement current I_d is defined as $I_d \equiv \varepsilon_0 \frac{d\Phi_E}{dt}$ and represents an effective current through a region of space in which an electric field is changing in time.

24.1

Two surfaces S_1 and S_2 near the plate of a capacitor are bounded by the same path P . The conduction current in the wire passes only through S_1 , which leads to a contradiction in Ampere's law that is resolved only if one postulates a displacement current through S_2 .

24.2

Because it exists only in the wires attached to the capacitor plates, the conduction current $I = dq/dt$ passes through the curved surface S_1 but not the flat surface S_2 . Only the displacement current $I_d = \epsilon_0 d\Phi_E/dt$ passes through S_2 . The two currents must be equal for continuity.

24.2 MAXWELL'S EQUATIONS

For simplicity we present **Maxwell's equations** as applied to free space, that is, in the absence of any dielectric or magnetic material. The four equations are

$$\oint \vec{E} \cdot d\vec{A} = \frac{q}{\epsilon_0} \quad \text{Gauss's law}$$

$$\oint \vec{B} \cdot d\vec{A} = 0 \quad (\text{can be considered}) \quad \text{Gauss's law for magnetism}$$

$$\oint \vec{E} \cdot d\vec{s} = -\frac{d\Phi_B}{dt} \quad \text{Faraday's law of induction}$$

$$\oint \vec{B} \cdot d\vec{s} = \mu_0 I + \epsilon_0 \mu_0 \frac{d\Phi_B}{dt} \quad \text{the generalized form of Ampere's law}$$

24.3 ELECTROMAGNETIC WAVES

24.3 (a) and (b)

The fields in an electromagnetic wave traveling at velocity \vec{c} in the positive x and t .

Representation of a sinusoidal electromagnetic wave moving in the positive x and t .

24.3 ELECTROMAGNETIC WAVES Cont'd

Electric field wave equation for electromagnetic waves in free space

$$\frac{\partial^2 E}{\partial^2 x^2} = \epsilon_0 \mu_0 \frac{\partial^2 E}{\partial^2 t^2} \longleftrightarrow E = E_{\max} \cos(kx - \omega t)$$

Magnetic field wave equation for electromagnetic waves in free space

$$\frac{\partial^2 B}{\partial^2 x^2} = \epsilon_0 \mu_0 \frac{\partial^2 B}{\partial^2 t^2} \longleftrightarrow B = B_{\max} \cos(kx - \omega t)$$

*In these expressions, E_{\max} and B_{\max} are the maximum values of the fields, the wave number $k = 2\pi/\lambda$, where λ is the wavelength, and the angular frequency $\omega = 2\pi f$, where f is the frequency.

24.3 ELECTROMAGNETIC WAVES Cont'd

Doppler Effect for electromagnetic waves

$$f' = f \sqrt{\frac{c + v}{c - v}}$$

where v is the relative speed between the source and the observer, c is the speed of light, f' is the frequency of light detected by the observer, and f is the frequency emitted by the source.

24.4 HERTZ'S DISCOVERIES

The coefficient of Q as the square of the angular frequency:

$$\omega^2 = \frac{1}{LC}$$

Therefore, the frequency of oscillation of an LC circuit, called the *resonance frequency*, is

$$f_0 = \frac{1}{2\pi\sqrt{LC}}$$

24.5 ENERGY CARRIED BY ELECTROMAGNETIC WAVES

Electromagnetic waves carry energy. The rate of flow of energy crossing a unit area is described by the **Poynting vector** \vec{S} , where

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

The average value of the Poynting vector for a plane electromagnetic wave has the magnitude

$$I = S_{avg} = \frac{E_{max} B_{max}}{2\mu_0} = \frac{E_{max}^2}{2\mu_0 c} = \frac{c B_{max}^2}{2\mu_0}$$

24.6 MOMENTUM AND RADIATION PRESSURE

Electromagnetic waves have momentum and exert pressure on surfaces on which they are incident. The pressure exerted by a normally incident wave on a totally reflecting surface is double that exerted on a surface that completely absorbs the incident wave.

The radiation pressure P exerted perfectly absorbing surface is

$$P = \frac{S}{c} \quad (\text{Complete absorption})$$

*If the surface totally reflects a normally incident wave, the pressure is doubled.

24.7 THE SPECTRUM OF ELECTROMAGNETIC WAVES

figure 24.12

24.8 POLARIZATION

The **electromagnetic spectrum** includes waves covering a broad range of frequencies and wavelengths. When polarized light of intensity I_0 is incident on a polarizing film the light transmitted through the film has an intensity equal to $I_0 \cos^2 \theta$, where θ is the angle between the transmission axis of the polarizing film and the electric field vector of the incident light.
