Chapter 25   Electromagnetic Waves

Outline

25-1   The production of Electromagnetic Waves
25-3   The Electromagnetic Spectrum
25-4   Energy and momentum in Electromagnetic Waves
25-5   Polarization
25-1 The production of Electromagnetic Waves

**Electromagnetic waves**: Visible light (440 ~ 700nm) is a kind of electromagnetic waves

**Electromagnetic waves are transverse waves**: the vibration of each point is vertical to the propagation direction.

An Electromagnetic wave consists of two vertical components: \( \vec{E} \) (electric filed) and \( \vec{B} \) (Magnetic field).

The electric field vector \( \vec{E} \), magnetic field \( \vec{B} \), and the propagation are all vertical each other!

The Electromagnetic waves travel through vacuum (air) at the same speed:

\[ C = 3.00 \times 10^8 \text{ m/s}, \quad \text{the speed of light！} \]
Direction of Propagation for Electromagnetic Waves

Point the fingers of your right hand in the direction of the \( \vec{E} \), curl your fingers toward \( \vec{B} \), and your thumb will point in the direction of the propagation.
CONCEPTUAL CHECKPOINT 25–1

An electromagnetic wave propagates in the positive y direction, as shown in the sketch. If the electric field at the origin is in the positive z direction, is the magnetic field at the origin in (a) the positive x direction, (b) the negative x direction, or (c) the negative y direction?
CONCEPTUAL CHECKPOINT 25–1

An electromagnetic wave propagates in the positive $y$ direction, as shown in the sketch. If the electric field at the origin is in the positive $z$ direction, is the magnetic field at the origin in (a) the positive $x$ direction, (b) the negative $x$ direction, or (c) the negative $y$ direction?

Reasoning and Discussion

Pointing the fingers of the right hand in the positive $z$ direction (the direction of $\vec{E}$), we see that in order for the thumb to point in the direction of propagation (the positive $y$ direction) the fingers must be curled toward the positive $x$ direction. Therefore, $\vec{B}$ points in the positive $x$ direction.

Answer:

(a) $\vec{B}$ is in the positive $x$ direction.
When white light passes through a prism, it spread out into a rainbow of different colors. This indicates that the electromagnetic waves have different wavelengths, since different colors have different wavelength.

The wavelength and frequency is associated each other as,

\[ c = f\lambda \]  \hspace{1cm} (25 - 4) 

Where \( c \) is the speed of the electromagnetic wavelength in vacuum and is a constant. \( C \) is in m/s.
\( \lambda \) is in m
\( f \) is in Hz.
Wavelength $\lambda$, frequency $f$, and propagation direction.
Example 25-3

Find the frequency of red light with a wavelength of 700.0 nm.

Solution

Since \( c = f \lambda \), we have,

\[
3.00 \times 10^8 \text{ m/s} = f (700.0 \times 10^{-9} \text{ m})
\]

\[
f = \frac{3.00 \times 10^8 \text{ m/s}}{700.0 \times 10^{-9} \text{ m}} = 4.29 \times 10^{14} \text{ Hz}
\]
Example 25-3
The spectrum of white light.
Figure 25-8
The Electromagnetic Spectrum
Energy and momentum in Electromagnetic Waves

Since energy density (energy per volume) of electric field (Section 20-6) is,

\[ u_E = \frac{1}{2} \varepsilon_0 E^2 \]

And since energy density of magnetic field (Section 23-9) is,

\[ u_B = \frac{1}{2 \mu_0} B^2 \]

As the electromagnetic wave is composed of electric and magnetic fields, the total energy density of the electromagnetic wave is

\[ u = u_B + u_E = \frac{1}{2} \varepsilon_0 E^2 + \frac{1}{2 \mu_0} B^2 \quad (25-5) \]
It can be shown that electric and magnetic energy densities are equal. So, one has

\[ u = \frac{1}{2} \varepsilon_0 E^2 + \frac{1}{2\mu_0} B^2 = \varepsilon_0 E^2 = \frac{1}{\mu_0} B^2 \]  \hspace{1cm} (25-6)

Since \( E \) and \( B \) are sinusoidal functions of the time, we must use RMS value to calculate the “average” value,

\[ u_{av} = \frac{1}{2} \varepsilon_0 E_{rms}^2 + \frac{1}{2\mu_0} B_{rms}^2 = \varepsilon_0 E_{rms}^2 = \frac{1}{\mu_0} B_{rms}^2 \]  \hspace{1cm} (25-7)

Where,

\[ E_{rms} = \frac{E_{\text{max}}}{\sqrt{2}} \]
\[ B_{rms} = \frac{B_{\text{max}}}{\sqrt{2}} \]  \hspace{1cm} (25-8)
The relationship of $E$ and $B$

Since,

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

from \hspace{1cm} (25-6)

We have

$$E = \frac{1}{\sqrt{\varepsilon_0 \mu_0}} B$$

**Pemittivity of free space** $\varepsilon_0 = 8.85 \times 10^{-12} \text{ C}^2/(\text{N} \cdot \text{m}^2)$ \hspace{1cm} (19-12)

**Permeability of free space** $\mu_0 = 4\pi \times 10^{-7} \text{ T} \cdot \text{m}/\text{A}$ \hspace{1cm} (22-8)

$$c = 1/\sqrt{\varepsilon_0 \mu_0} = 3.00 \times 10^8 \text{ m/s}$$

so we eventually have

$$E = cB \hspace{1cm} (25-9)$$

$$E_{rms} = cB_{rms}$$
Exercise 25-3

At a given instant of time, the electric field in a beam of sunlight has a magnitude of 510 N/C. What is the magnitude of the magnetic field at this instant?

Solution:

\[ E = Bc \]

\[ 510 \text{ N/C} = B(3.00 \times 10^8 \text{ m/s}) \]

\[ B = \frac{E}{c} = \frac{510 \text{ N/C}}{3.00 \times 10^8 \text{ m/s}} = 1.7 \times 10^{-6} \text{ T} \]
**Intensity I**

The amount of the energy a wave delivers to a unit area in a unit time is called Intensity $I$. Also $I = P/A$

In figure 25-9, the intensity $I$ is

$$I = \frac{\Delta U}{A \Delta t} = \frac{u(Ac \Delta t)}{A \Delta t} = uc$$

Substitute (25-6), we have

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

(25-10)

To calculate the average intensity, we only need to replace the $E$ and $B$ with their rms value in the above formula.
Example 25-4

A garage is illuminated by a single light bulb. If the bulb radiate light uniformly in all directions, and consumes an average electrical power of 50.0 W. Assume that 5.00% of the electric power consumed by the bulb is converted to light. What are

(a) The average intensity of the bulb at a distance of 1.00 m from the bulb, and

(b) the rms values of E and B at a distance of 1.00 m from the bulb?
Active Example 25-1

A small laser emits a cylindrical beam of light 1.00 mm in diameter with average power of 5.00 mW. Find the maximum values of E and B in the beam.
Summary

1) Electromagnetic waves are transverse waves and it consists of two vertical components: electric field and magnetic field.

2) Energy in Electromagnetic Waves