Chapter 24  Electromagnetic Waves

Goals for Chapter 23

- To understand electromagnetic waves, the speed of light, and the electromagnetic spectrum.
- To characterize sinusoidal waves and determine their energy.
- To understand Doppler effect.
- To study polarization.

James Clerk Maxwell   1831 – 1879
- Electricity and magnetism were originally thought to be unrelated
- in 1865, James Clerk Maxwell provided a mathematical theory that showed a close relationship between all electric and magnetic phenomena

Heinrich Hertz    1857 – 1894
- First to generate and detect electromagnetic waves in a laboratory setting
- Showed radio waves could be reflected, refracted and diffracted
- The unit Hz is named for him

Maxwell’s Starting Points
- Electric field lines originate on positive charges and terminate on negative charges
- Magnetic field lines always form closed loops - they do not begin or end anywhere
- A varying magnetic field induces an emf and hence an electric field (Faraday’s Law)
- Magnetic fields are generated by moving charges or currents (Ampère’s Law)

Maxwell’s Predictions
- Maxwell used these starting points and a corresponding mathematical framework to prove that electric and magnetic fields play symmetric roles in nature
- He hypothesized that a changing electric field would produce a magnetic field
- Maxwell calculated the speed of light to be $3 \times 10^8$ m/s
- He concluded that visible light and all other electromagnetic waves consist of fluctuating electric and magnetic fields, with each varying field inducing the other

24.1 The Nature of Electromagnetic Waves

Two straight wires connected to the terminals of an AC generator can create an electromagnetic wave.

The current used to generate the electric wave creates a magnetic field.

Only the electric wave traveling to the right is shown here.
24.1 The Nature of Electromagnetic Waves

Notice that the magnetic field is perpendicular to the page whereas the electric field lies in the plane of the page. Combine both electric field and magnetic field together forms the electromagnetic wave generated by oscillating current on the linear antenna. Here are different ways to show the electromagnetic wave.

Unlike the Static electric field or static magnetic field, the electromagnetic fields generated by an antenna is a propagating wave. The EM wave consists of E-field and B-field that is perpendicular to each other and also perpendicular to the direction of travel.

This picture shows the wave of the radiation field far from the antenna. It is approximated as a plane wave.

The speed of an electromagnetic wave in a vacuum is:
\[ c = 3.00 \times 10^8 \text{ m/s} \]

A radio wave can be detected with a receiving antenna wire that is parallel to the electric field.

The frequencies of AM radio lie between 545 kHz and 1604 kHz.
The frequencies of FM radio lie between 88 MHz and 108 MHz.
The frequencies of VHF TV signals lie between 54 MHz to 88 MHz.
The frequencies of UHF TV signals lie between 174 and 216 MHz.

With a receiving antenna in the form of a loop, the magnetic field of a radio wave can be detected.

Like all waves, electromagnetic waves have a wavelength and frequency, related by:
\[ c = f\lambda \]
Wavelengths and Information

• These are images of the Crab Nebula
• They are (clockwise from upper left) taken with
  – x-rays
  – visible light
  – radio waves
  – infrared waves

24.2 The Electromagnetic Spectrum

Example 1 The Wavelength of Visible Light

Find the range in wavelengths for visible light in the frequency range between $4.0 \times 10^{14}$ Hz and $7.9 \times 10^{14}$ Hz.

\[
\lambda = \frac{c}{f}
\]

\[
\lambda = \frac{3.00 \times 10^8 \text{ m/s}}{4.0 \times 10^{14} \text{ Hz}} = 7.5 \times 10^{-7} \text{ m} = 750 \text{ nm}
\]

\[
\lambda = \frac{3.00 \times 10^8 \text{ m/s}}{7.9 \times 10^{14} \text{ Hz}} = 3.8 \times 10^{-7} \text{ m} = 380 \text{ nm}
\]

24.3 The Speed of Light

Conceptual Example 2 The Diffraction of AM and FM Radio Waves

Diffraction is the ability of a wave to bend around an obstacle or the edges of an opening. Would you expect AM or FM radio waves to bend more readily around an obstacle such as a building?

Answer: Since AM radio waves have longer wavelengths than the FM radio waves, they will be more easily diffracted.

The concept of light as a wave is supported by experiments and will be discussed more in Chapter 27. But light also behave like discrete particles in some experiments. Wave theories and particle theories of light have been around for hundred of years. It is now widely accepted that light can exhibit both wave and particle behavior.

24.3 The Speed of Light

Conceptual Example 3 Looking Back in Time

A supernova is a violent explosion that occurs at the death of certain stars. The figure shows a photograph of the sky before and after the 1987 supernova. This occurred in a galaxy $1.66 \times 10^{21}$ meter away.

How long it takes for the light to reach earth?

\[
t = \frac{d}{c} = \frac{1.66 \times 10^{21}}{3.00 \times 10^8} = 5.53 \times 10^8 \text{ s} = 175,000 \text{ years}
\]

Maxwell’s prediction of the speed of light (or any electromagnetic wave).

\[
c = \frac{1}{\sqrt{\varepsilon_0 \mu_0}} = \frac{1}{\sqrt{(8.85 \times 10^{-12} \text{ C}^2/\text{N} \cdot \text{m}^2)(4\pi \times 10^{-7} \text{ T} \cdot \text{m/A})}} = 3.00 \times 10^8 \text{ m/s}
\]
Properties of an electromagnetic wave

- Electromagnetic waves travel at the speed of light
- Electromagnetic waves require no medium
- Electromagnetic waves are transverse waves
- The ratio of the electric field to the magnetic field is equal to the speed of light
- Electromagnetic waves carry energy as they travel through space, and this energy can be transferred to objects placed in their path.

24.4 The Energy Carried by Electromagnetic Waves

Electromagnetic waves, like water waves, carry energy. The energy is carried by the electric and magnetic fields.

The total energy density carried by an electromagnetic wave

\[ u = \frac{\text{Total energy}}{\text{Volume}} = \frac{1}{2} \varepsilon_0 E^2 + \frac{1}{2 \mu_0} B^2 \]

In an electromagnetic wave, the energy carried by electric field is the same as the energy carried by magnetic field.

\[ \frac{1}{2} \varepsilon_0 E^2 = \frac{1}{2 \mu_0} B^2 \]

So the total energy density is:

\[ u = \varepsilon_0 E^2 = \frac{B^2}{\mu_0} \]

So the intensity of the EM radiation is the speed of light times the energy density.

\[ S = cu = c \left( \frac{1}{2} \varepsilon_0 E^2 + \frac{1}{2 \mu_0} B^2 \right) \]

\[ S = c \varepsilon_0 E^2 = \frac{c}{\mu_0} B^2 \]

Example 5 Power and intensity

A tiny light source emitting light uniformly in all directions as shown. At a distance of 2.50 m from this source, the rms electric field strength of the light is 19.0 N/C. Determine the average power of the light emitted by the source.

The average power is

\[ \bar{P} = \bar{S} \cdot (4 \pi r^2) \]

The average intensity is

\[ \bar{S} = c \varepsilon_0 E_{\text{rms}}^2 \]

So the average power becomes

\[ \bar{P} = (3 \times 10^8)(8.85 \times 10^{-12})(19.0) \cdot 4\pi (1.5)^2 = 75.3 \text{ W} \]
The Doppler effect is the change in frequency or pitch of the sound detected by an observer because the sound source and the observer have different velocities with respect to the medium of sound propagation.

**Example: The sound of a passing train**

A high-speed train is traveling at a speed of 44.7 m/s when the engineer sounds the 415-Hz warning horn. The speed of sound is 343 m/s. What are the frequency and wavelength of the sound, as perceived by a person standing at the crossing, when the train is (a) approaching and (b) leaving the crossing?

**Approaching**

\[
f_o = f_s \left( \frac{1}{1 - \frac{v_s}{v}} \right) = 415 \text{ Hz} \left( \frac{1}{1 - \frac{44.7}{343}} \right) = 477 \text{ Hz}
\]

**Moving away**

\[
f_o = f_s \left( \frac{1}{1 + \frac{v_s}{v}} \right) = 415 \text{ Hz} \left( \frac{1}{1 + \frac{44.7}{343}} \right) = 367 \text{ Hz}
\]

**Doppler effect and electromagnetic waves**

Electromagnetic waves also can exhibit a Doppler effect, but it differs for two reasons:

a) Sound waves require a medium, whereas electromagnetic waves do not.

b) For sound, it is the motion relative to the medium that is important.

For electromagnetic waves, only the relative motion of the source and observer is important.

\[
f_o = f_s \left( 1 \pm \frac{v_{rel}}{c} \right) \quad \text{if} \quad v_{rel} \ll c
\]

**Example: Radar guns and speed traps**

The radar gun of a police car emits an electromagnetic wave with a frequency of \(8.0 \times 10^9\) Hz. The approach is essentially head on. The wave from the gun reflects from the speeding car and returns to the police car, where on-board equipment measures its frequency to be greater than the emitted wave by 2100 Hz. Find the speed of the car with respect to the highway. The police car is parked.
The Inverse-Square Dependence of $S$

A point source of light, or any radiation, spreads out in all directions:

$S_{av} = \frac{P_{source}}{4\pi r^2}$

Example: An observer is 1.8 m from a point light source whose average power $P = 250$ W. Calculate the rms fields in the position of the observer.

Av. Intensity of light at distance $r$ is $S = \frac{P_{source}}{(4\pi r^2)}$

$I = \frac{P_{source}}{4\pi r^2}$

$E_{rms}^2 = \frac{I}{\mu_0 c}$

$E_{rms} = \sqrt{\frac{I}{4\pi r^2}}$ m

$E_{max} = 48$ V/m

$B = \frac{E_{rms}}{c} = 0.16\mu T$

Polarization

The direction of polarization of a wave is the direction of the electric field. Most light is randomly polarized, which means it contains a mixture of waves of different polarizations.

Polarization

Frequency and wavelength of an electromagnetic wave

$\lambda = \frac{c}{f}$

The direction of the electric field $E$ is the direction of polarization. In polarized light, the electric field fluctuates along a single direction.
**Polarization**

A polarizer lets through light of only one polarization:

- Produce polarized from unpolarized light

Transmitted light has its $E$ in the direction of the polarizer’s transmission axis.

$$E = E_0 \cos \theta$$

hence,

$$S = S_0 \cos^2 \theta \quad - \text{Malus’ Law}$$

Example: Using Polarizers and Analyzers

What value of $\theta$ should be used so the average intensity of the polarized light reaching the photocell is one-tenth the average intensity of the unpolarized light?

$$\frac{1}{10} S_0 = \left( \frac{1}{2} S_0 \right) \cos^2 \theta$$

$$\frac{1}{10} = \cos^2 \theta$$

$$\cos \theta = \sqrt{\frac{1}{10}}$$

$$\theta = 63.4^\circ$$

**Polarizers and Analyzers**

When polarizers (or polarizer and analyzer) are crossed, the intensity of the transmitted light is reduced to zero.

Suppose that a third piece of polarizing material is inserted between the polarizer and analyzer. Does light now reach the photocell?

Yes

**Polarization Changes due to Scattering of Light by a Molecule**