10.8 Electromagnetic Waves and Light

DID YOU KNOW?

James Clerk Maxwell

James Clerk Maxwell (1831–1879) is regarded as one of the greatest physicists the world has known. Einstein stated that his work resulted in the most profound changes in physics since Newton. Maxwell died young and failed to see the corroboration of his theory by Hertz's laboratory creation of radio waves. His work paved the way for Einstein's special theory of relativity and helped usher in the other major innovation of twentieth-century physics, quantum theory.

Once Oersted and Faraday had established the basic relationships between electricity and magnetism in the early nineteenth century, it was not long before others began to extend electromagnetic theory to closely related phenomena. One of the great scientific achievements of the nineteenth century was the discovery that waves of electromagnetic energy travel through space.

In 1864, the Scottish physicist and mathematician James Clerk Maxwell summarized his theories about electromagnetic fields as four basic relationships, appropriately known as Maxwell's equations of electromagnetism. Although the equations require mathematical notation beyond the scope of this text, we can summarize Maxwell's main ideas in words:

1. The distribution of electric charges, in space, produces an electric field.
2. Magnetic field lines are continuous loops without beginning or end. Electric field lines, on the other hand, begin and end on electric charges.
3. A changing electric field produces a magnetic field.
4. A changing magnetic field produces an electric field.

These statements should already be familiar to you, with the possible exception of 4. It is basically Faraday's law of electromagnetic induction, which, as you recall from Chapter 8, states that a changing magnetic field in the region of a conductor induces a potential difference in the conductor, causing a current to flow. For such an induced current to flow through a conductor, there must be an electric field present in the conductor, causing its charged particles to move.

These two converse phenomena—a changing electric field producing a magnetic field and a changing magnetic field producing an electric field—led Maxwell to an inevitable conclusion. He predicted that as they continuously changed, interacting electric and magnetic fields would actually travel through space in the form of electromagnetic waves. Further, Maxwell worked out the essential characteristics of such a wave:

- Electromagnetic waves are produced whenever electric charges are accelerated. The accelerated charge loses energy that is carried away in the electromagnetic wave.
- If the electric charge is accelerated in periodic motion, the frequency of the electromagnetic waves produced is exactly equal to the frequency of oscillation of the charge.
- All electromagnetic waves travel through a vacuum at a common speed ($c = 3.00 \times 10^8$ m/s), and obey the universal wave equation, $c = f\lambda$.
- Electromagnetic waves consist of electric and magnetic fields oscillating in phase, perpendicular to each other, and both at 90° to the direction of propagation of the wave, as depicted in **Figure 1**.
- Electromagnetic waves exhibit the properties of interference, diffraction, polarization, and refraction and can carry linear and angular momentum.
- All electromagnetic waves can be polarized, and radiation where the electric field vector is in only one plane is said to be plane-polarized. (The plane of polarization is the plane containing all of the changing electric field vectors.)

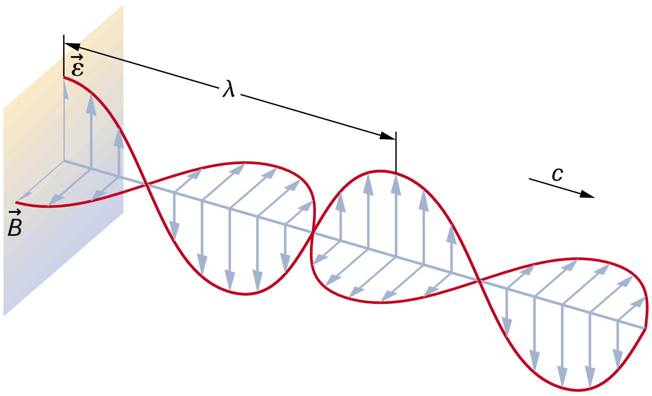

Figure 1
The electric and magnetic fields are perpendicular to one another and to the direction of radiation.

Such an electromagnetic wave was first produced and detected in the laboratory by the German physicist Heinrich Hertz (1857–1894) in 1887, not long after Maxwell's death. Using a spark gap, across which electric charges moved rapidly back and forth, Hertz was able to generate electromagnetic waves whose frequency was about 1 MHz. He detected these waves from some distance away, using as an antenna a loop of wire in which a current was produced when a changing magnetic field passed through (**Figure 2**).

DID YOU KNOW?

The Hertz
The SI unit for frequency, equivalent to "one cycle per second," in strict mathematical accuracy "s^{-1}," is named for Hertz: 1 s^{-1} = 1 Hz.

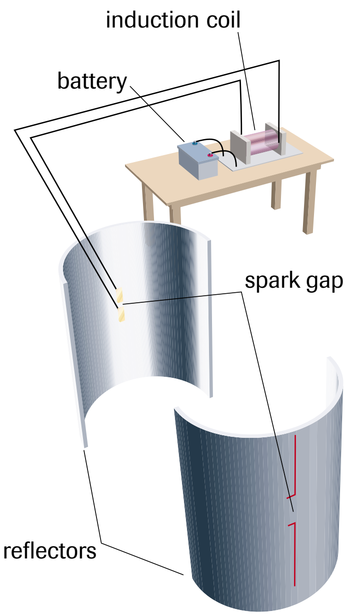

Figure 2
Hertz's experimental setup

Hertz was also able to show that these waves travelled at the speed of light in a vacuum and that they exhibited the characteristic wave phenomena: reflection, refraction, interference, and even polarization.

Hertz called his waves **radio waves**. His discovery lay the experimental foundation for engineering by Marconi and other radio pioneers, who first transmitted radio waves across the English Channel in 1889. Despite predictions that Earth's curvature would make long-distance communication by electromagnetic waves impossible, Marconi spanned the Atlantic in 1901. At what is now called Signal Hill, in St. John's, Newfoundland, he received a Morse code "S" sent from Cornwall, England, 3360 km away.

radio waves electromagnetic waves in the frequency range 10^4 to 10^{10} Hz; used in radio and TV transmission

The prediction made by Maxwell, and its verification by Hertz, that electromagnetic waves travel at the speed of light was of paramount significance. Although it had been accepted for over half a century that light behaves as a wave, it had remained unclear what, in concrete physical terms, the wave was. Maxwell, on the basis of his calculated speed for electromagnetic waves, argued that light waves must be electromagnetic. After Hertz's discovery of radio waves, Maxwell's claim was soon widely accepted.

The Electromagnetic Spectrum

Visible light and radio waves occupy only two small ranges of all the frequencies possible for oscillating electric and magnetic fields. Today, we know that there is a broad range of frequencies of electromagnetic waves—the electromagnetic spectrum—all having the basic characteristics predicted by Maxwell. **Table 1** lists the names that have been given to the various regions of this spectrum and the approximate frequency range for each region, with a brief description of the type of accelerated charge that leads to the formation of each.

A sample problem will illustrate how traditional wave analysis can be used to solve problems using various regions of the spectrum.

Table 1 The Electromagnetic Spectrum

Type of Radiation	Frequency Range	Origin of Radiation	Applications or Effects of Radiation
low frequency AC	60 Hz	weak radiation emitted from conductors of AC power	causes interference in radio reception when passing near high-voltage transmission lines
radio, radar, TV	$10^4 - 10^{10}$ Hz	oscillations in electric circuits containing inductive and capacitive components	transmission of radio and TV communication signals; ship and aircraft navigation by radar; reception of radio waves from space by radio telescopes; control of satellites, space probes, and guided missiles
microwaves	$10^9 - 10^{12}$ Hz	oscillating currents in special tubes and solid-state devices	long-range transmission of TV and other telecommunication information; cooking in microwave ovens
infrared	$10^{11} - 4 \times 10^{14}$ Hz	transitions of outer electrons in atoms and molecules	causes the direct heating effect of the Sun and other radiant heat sources; is used for remote sensing and thermography
visible light	$4 \times 10^{14} - 8 \times 10^{14}$ Hz	higher-energy transitions of outer electrons in atoms	radiation that can be detected by the human eye, giving the sensation of "seeing"
ultraviolet	$8 \times 10^{14} - 10^{17}$ Hz	even higher energy transitions of outer electrons in atoms	causes fluorescence in some materials; causes "tanning" of human skin; kills bacteria; aids in the synthesis of vitamin D by the human body
X rays	$10^{15} - 10^{20}$ Hz	transitions of inner electrons of atoms or the rapid deceleration of high-energy free electrons	penetrate soft tissue easily but are absorbed by denser tissue, like bones and teeth, to produce X-ray images of internal body structures; used for radiation therapy and nondestructive testing in industry
gamma rays	$10^{19} - 10^{24}$ Hz	nuclei of atoms, both spontaneous and from the sudden deceleration of very high-energy particles from accelerators	treatment for localized cancerous tumours
cosmic rays	$> 10^{24}$ Hz	bombardment of Earth's atmosphere by very high-energy particles from space	responsible for auroras

SAMPLE problem

Microwaves with a wavelength of 1.5 cm are used to transmit television signals coast to coast, through a network of relay towers.

(a) What is the frequency of these microwaves?

(b) How long does it take a microwave signal to cross the continent from St. John's, Newfoundland, to Victoria, British Columbia, a distance of approximately 5.0×10^3 km?

Solution

(a) $\lambda = 1.5$ cm

$v = c = 3.00 \times 10^8$ m/s

$f = ?$

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

$$= \frac{3.00 \times 10^8 \text{ m/s}}{1.5 \times 10^{-2} \text{ m}}$$

$$f = 2.0 \times 10^{10} \text{ Hz}$$

The frequency is 2.0×10^{10} Hz.

(b) $\Delta d = 5.0 \times 10^3 \text{ km} = 5.0 \times 10^6$ m

$\Delta t = ?$

$$\Delta d = v\Delta t$$

$$= c\Delta t$$

$$\Delta t = \frac{\Delta d}{c}$$

$$= \frac{5.0 \times 10^6 \text{ m}}{3.0 \times 10^8 \text{ m/s}}$$

$$\Delta t = 1.6 \times 10^{-2} \text{ s}$$

The time required is 1.6×10^{-2} s.

Practice

Understanding Concepts

1. Calculate the wavelength of the signal radiated by an FM broadcast station with a frequency of 107.1 MHz.

2. Your class is touring a university physics lab. You notice an X-ray machine operating at 3.00×10^{17} Hz. What is the wavelength of the X rays produced?

3. Calculate the period of the light emitted by a helium–neon laser whose wavelength is 638 nm.

4. How many wavelengths of the radiation emitted by a 6.0×10^1 Hz electrical transmission line would it take to span the North American continent (a distance of approximately 5.0×10^3 km)?

Answers

1. 2.80 m
2. 1.00×10^{-9} m
3. 2.13×10^{-15} s
4. 1.0

In this unit, we started with a systematic inventory of the properties of light but came to the conclusion that light is just one of the many radiations in the electromagnetic spectrum, all possessing the same set of essential properties.

SUMMARY Electromagnetic Waves and Light

- Maxwell postulated and Hertz proved that light and all radiations travel as electromagnetic waves through space at the speed of light (3.00×10^8 m/s).
- Electromagnetic waves consist of electric and magnetic fields that oscillate in phase and perpendicular to each other and to the direction of wave propagation.
- Electromagnetic waves exhibit the properties of interference, diffraction, polarization, reflection, and refraction.
- The electromagnetic spectrum makes up all the radiations that originate from a source with a changing electric or magnetic field.
- The electromagnetic spectrum consists of radio waves (including microwaves), infrared waves, visible light, ultraviolet light, X rays, gamma rays, and cosmic rays.

Section 10.8 Questions

Understanding Concepts

1. Calculate the quantity indicated for each of the following electromagnetic waves:
   (a) the frequency of an 1.80-cm wavelength microwave
   (b) the wavelength of a 3.20×10^{10}-Hz radar signal
   (c) the distance between adjacent maxima of magnetic field strength in the electromagnetic wave created by a 60.0-Hz transmission line
   (d) the frequency of red visible light, of wavelength 6.5×10^{-7} nm
2. Two football fans are listening to the Grey Cup game on the radio, one in Montreal, where the game is being played, the other in Inuvik, Northwest Territories, 6.00×10^3 km away. The distant signal is transmitted by microwave, through a communications satellite at an altitude of 3.6×10^4 km. Making whatever assumptions seem reasonable, determine how much sooner the fan in Montreal hears the results of any play.
3. A slit 6.0 cm wide is placed in front of a microwave source operating at a frequency of 7.5 GHz. Calculate the angle (measured from the central maximum) of the first minimum in the diffraction pattern.
4. The first radio amateurs used high-voltage electrical arcs, as Hertz did, to generate radio waves and communicate with one another. Why did this soon become an unworkable situation?

Applying Inquiry Skills

5. How could you use a small portable radio to locate a high-voltage leak in the ignition system of a car?

Making Connections

6. Why is it that when television correspondents are interviewed live on the other side of the planet, there is a short delay before their responses are heard?
7. Television and radio waves can reflect from nearby mountains or from airplanes. Such reflections can interfere with the direct signal from the station.
   (a) Determine what kind of interference will occur when 75-MHz television signals arrive at a receiver directly from a distant station and are also reflected from an airplane 134 m directly above the receiver. (Assume a $\frac{\lambda}{2}$ change in phase of the wave upon reflection.) Explain your reasoning.
   (b) Determine what kind of interference will occur if the plane is 42 m closer to the receiver. Explain your reasoning.