Summary

James Clerk Maxwell synthesized an elegant theory in which all electric and magnetic phenomena could be described using four equations, now called **Maxwell's equations**. They are based on earlier ideas, but Maxwell added one more—that a changing electric field produces a magnetic field.

Maxwell's theory predicted that transverse **electromagnetic** (EM) **waves** would be produced by accelerating electric charges, and these waves would propagate (move) through space at the speed of light, given by the formula

$$c = \frac{1}{\sqrt{\epsilon_0 \mu_0}}. \tag{22–3}$$

The oscillating electric and magnetic fields in an EM wave are perpendicular to each other and to the direction of propagation. These waves are waves of fields, not matter, and can propagate in empty space.

The wavelength λ and frequency f of EM waves are related to their speed c by

$$c = \lambda f, \tag{22–4}$$

just as for other waves.

After EM waves were experimentally detected, the idea that light is an EM wave (of very high frequency) became generally accepted. The **electromagnetic spectrum** includes EM waves of a wide variety of wavelengths, from microwaves and radio waves to visible light to X-rays and gamma rays, all of which travel through space at a speed $c = 3.0 \times 10^8$ m/s.

[*The average *intensity* (W/m^2) of an EM wave is

$$\bar{I} = \frac{1}{2}\epsilon_0 c E_0^2 = \frac{1}{2}\frac{c}{\mu_0}B_0^2 = \frac{1}{2}\frac{E_0 B_0}{\mu_0}, \tag{22–8}$$

where E_0 and B_0 are the peak values of the electric and magnetic fields, respectively, in the wave.]

[*EM waves carry momentum and exert a *radiation pressure* proportional to the intensity I of the wave.]

Questions

1. The electric field in an EM wave traveling north oscillates in an east–west plane. Describe the direction of the magnetic field vector in this wave.
2. Is sound an electromagnetic wave? If not, what kind of wave is it?
3. Can EM waves travel through a perfect vacuum? Can sound waves?
4. When you flip a light switch on, does the light go on immediately? Explain.
5. Are the wavelengths of radio and television signals longer or shorter than those detectable by the human eye?
6. When you connect two loudspeakers to the output of a stereo amplifier, should you be sure the lead-in wires are equal in length so that there will not be a time lag between speakers? Explain.
7. In the electromagnetic spectrum, what type of EM wave would have a wavelength of 10^3 km? 1 km? 1 m? 1 cm? 1 mm? 1 μm?
8. Can radio waves have the same frequencies as sound waves (20 Hz–20,000 Hz)?

* 9. Can two radio or TV stations broadcast on the same carrier frequency? Explain.

* 10. If a radio transmitter has a vertical antenna, should a receiver's antenna (rod type) be vertical or horizontal to obtain best reception?

* 11. The carrier frequencies of FM broadcasts are much higher than for AM broadcasts. On the basis of what you learned about diffraction in Chapter 11, explain why AM signals can be detected more readily than FM signals behind low hills or buildings.

* 12. Discuss how cordless telephones make use of EM waves. What about cell phones?

* 13. A lost person may signal by flashing a flashlight on and off using Morse code. This is actually a modulated EM wave. Is it AM or FM? What is the frequency of the carrier, approximately?

Problems

22–1 Changing $\vec{E}$ Produces $\vec{B}$

* 1. (II) At a given instant, a 1.8-A current flows in the wires connected to a parallel-plate capacitor. What is the rate at which the electric field is changing between the plates if the square plates are 1.60 cm on a side?

* 2. (II) A 1200-nF capacitor with circular parallel plates 2.0 cm in diameter is accumulating charge at the rate of 35.0 mC/s at some instant in time. What will be the magnitude of the induced magnetic field 10.0 cm radially outward from the center of the plates? What will be the magnitude of the field after the capacitor is fully charged?

22–2 EM Waves

3. (I) If the magnetic field in a traveling EM wave has a peak magnitude of 17.5 nT at a given point, what is the peak magnitude of the electric field?
4. (I) In an EM wave traveling west, the B field oscillates vertically and has a frequency of 80.0 kHz and an rms strength of 6.75×10^{-9} T. What are the frequency and rms strength of the electric field, and what is its direction? [*Hint*: see Fig. 22–7.]

22–3 and 22–4 EM Spectrum and Speed

5. (I) What is the frequency of a microwave whose wavelength is 1.60 cm?
6. (I) What is the wavelength of a 29.75×10^9-Hz radar signal?
7. (I) An EM wave has frequency 9.66×10^{14} Hz. What is its wavelength, and how would we classify it?
8. (I) An EM wave has a wavelength of 650 nm. What is its frequency, and how would we classify it?
9. (I) How long does it take light to reach us from the Sun, 1.50×10^8 km away?

10. (I) A widely used "short-wave" radio broadcast band is referred to as the 49-m band. What is the frequency of a 49-m radio signal?

11. (II) Our nearest star (other than the Sun) is 4.2 light-years away. That is, it takes 4.2 years for the light it emits to reach Earth. How far away is it in meters?

12. (II) A light-year is a measure of distance (not time). How many meters does light travel in a year?

13. (II) How long would it take a message sent as radio waves from Earth to reach Mars (*a*) when nearest Earth, (*b*) when farthest from Earth? [*Hint*: see Table 5–2, p. 125.]

14. (II) What is the minimum angular speed at which Michelson's eight-sided mirror would have had to rotate to reflect light into an observer's eye by succeeding mirror faces (Fig. 22–10)?

15. (II) A student wants to scale down Michelson's light-speed experiment to a size that will fit in one room. A six-sided mirror is available, and the stationary mirror can be mounted 12 m from the rotating mirror. If the arrangement is otherwise as shown in Fig. 22–10, at what minimum rate must the mirror rotate?

16. (II) Who will hear the voice of a singer first—a person in the balcony 50.0 m away from the stage (Fig. 22–19), or a person 3000 km away at home whose ear is next to the radio? How much sooner? Assume that the microphone is a few centimeters from the singer and the temperature is 20°C.

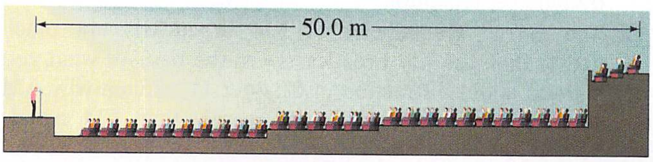

FIGURE 22–19 Problem 16.

17. (II) Pulsed lasers used in science and medicine produce very short bursts of electromagnetic energy. If the laser light wavelength is 1062 nm (this corresponds to a Neodymium-YAG laser), and the pulse lasts for 32 picoseconds, how many wavelengths are found within the laser pulse? How short would the pulse need to be to fit only one wavelength?

* 22–5 Energy in EM Waves

* **18.** (I) The $\vec{\mathbf{E}}$ field in an EM wave in free space has a peak of 21.8 mV/m. What is the average rate at which this wave carries energy across unit area per unit time?

* **19.** (II) The magnetic field in a traveling EM wave has an rms strength of 28.5 nT. How long does it take to deliver 235 J of energy to 1.00 cm^2 of a wall that it hits perpendicularly?

* **20.** (II) How much energy is transported across a 1.00-cm^2 area per hour by an EM wave whose E field has an rms strength of 38.6 mV/m?

* **21.** (II) A spherically spreading EM wave comes from a 1200-W source. At a distance of 10.0 m, what is the average intensity, and what is the rms value of the electric field?

* **22.** (II) A 12.8-mW laser puts out a narrow beam 1.75 mm in diameter. What are the average (rms) values of E and B in the beam?

* **23.** (II) Estimate the average power output of the Sun, given that about 1350 W/m^2 reaches the upper atmosphere of the Earth.

* **24.** (II) If the amplitude of the B field of an EM wave is 2.5×10^{-7} T, (*a*) what is the amplitude of the E field? (*b*) What is the average power per unit area of the EM wave?

* **25.** (II) A high-energy pulsed laser emits a 1.0-ns-long pulse of average power 2.8×10^{11} W. The beam is 2.2×10^{-3} m in radius. Determine (*a*) the energy delivered in each pulse, and (*b*) the rms value of the electric field.

* 22–6 Radiation Pressure

* **26.** (II) Estimate the radiation pressure due to a 100-W bulb at a distance of 8.0 cm from the center of the bulb. Estimate the force exerted on your fingertip if you place it at this point.

* 22–7 Radio, TV

* **27.** (I) What is the range of wavelengths for (*a*) FM radio (88 MHz to 108 MHz) and (*b*) AM radio (535 kHz to 1700 kHz)?

* **28.** (I) Estimate the wavelength for 1.9-GHz cell phone reception.

* **29.** (I) Compare 940 on the AM dial to 94 on the FM dial. Which has the longer wavelength, and by what factor is it larger?

* **30.** (I) What are the wavelengths for two TV channels that broadcast at 54.0 MHz (Channel 2) and 806 MHz (Channel 69)?

* **31.** (I) The variable capacitor in the tuner of an AM radio has a capacitance of 2800 pF when the radio is tuned to a station at 550 kHz. What must the capacitance be for a station near the other end of the dial, 1610 kHz?

* **32.** (I) The oscillator of a 96.1-MHz FM station has an inductance of 1.8 μH. What value must the capacitance be?

* **33.** (II) A certain FM radio tuning circuit has a fixed capacitor $C = 840$ pF. Tuning is done by a variable inductance. What range of values must the inductance have to tune stations from 88 MHz to 108 MHz?

* **34.** (II) An amateur radio operator wishes to build a receiver that can tune a range from 14.0 MHz to 15.0 MHz. A variable capacitor has a minimum capacitance of 82 pF. (*a*) What is the required value of the inductance? (*b*) What is the maximum capacitance used on the variable capacitor?

* **35.** (II) A satellite beams microwave radiation with a power of 10 kW toward the Earth's surface, 550 km away. When the beam strikes Earth, its circular diameter is about 1500 m. Find the rms electric field strength of the beam.

* **36.** (III) A 1.60-m-long FM antenna is oriented parallel to the electric field of an EM wave. How large must the electric field be to produce a 1.00-mV (rms) voltage between the ends of the antenna? What is the rate of energy transport per square meter?

General Problems

37. If the Sun were to disappear or somehow radically change its output, how long would it take for us on Earth to learn about it?

38. Light is emitted from an ordinary lightbulb filament in wave-train bursts about 10^{-8} s in duration. What is the length in space of such wave trains?

39. (*a*) How long did it take for a message sent from Earth to reach the first astronauts on the Moon? (*b*) How long will it take for a message from Earth to reach the first astronauts who arrive on Mars; assume Mars is at its closest approach to Earth (78×10^6 km)?

40. A radio voice signal from the *Apollo* crew on the Moon (Fig. 22–20) was beamed to a listening crowd from a radio speaker. If you were standing 25 m from the loudspeaker, what was the total time lag between when you heard the sound and when the sound left the Moon?

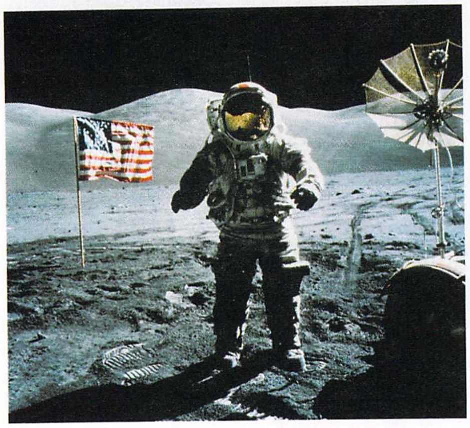

FIGURE 22–20 Problem 40.

* 41. Cosmic microwave background radiation fills all space with an average energy density of $4 \times 10^{-14}\,\text{J/m}^3$. (*a*) Find the rms value of the electric field associated with this radiation. (*b*) How far from a 10-kW radio transmitter emitting uniformly in all directions would you find a comparable value?

* 42. What are E_0 and B_0 2.00 m from a 95-W light source? Assume the bulb emits radiation of a single frequency uniformly in all directions.

* 43. Estimate the rms electric field in the sunlight that hits Mars, knowing that the Earth receives about $1350\,\text{W/m}^2$ and that Mars is 1.52 times farther from the Sun (on average) than is the Earth.

* 44. At a given instant in time, a traveling EM wave is noted to have its maximum magnetic field pointing west and its maximum electric field pointing south. In which direction is the wave traveling? If the rate of energy flow is $560\,\text{W/m}^2$, what are the maximum values for the two fields?

* 45. Estimate how long an AM antenna would have to be if it were (*a*) $\frac{1}{2}\lambda$ or (*b*) $\frac{1}{4}\lambda$. AM radio is roughly 1 MHz (530 kHz to 1.7 MHz).

* 46. How large an emf (rms) will be generated in an antenna that consists of a 380-loop circular coil of wire 2.2 cm in diameter if the EM wave has a frequency of 810 kHz and is transporting energy at an average rate of $1.0 \times 10^{-4}\,\text{W/m}^2$ at the antenna? [*Hint*: you can use Eq. 21–5 for a generator, since it could be applied to an observer moving with the coil so that the magnetic field is oscillating with the frequency $f = \omega/2\pi$.]

* 47. The average intensity of a particular TV station's signal is $1.0 \times 10^{-13}\,\text{W/m}^2$ when it arrives at a 33-cm-diameter satellite TV antenna. (*a*) Calculate the total energy received by the antenna during 6.0 hours of viewing this station's programs. (*b*) What are the amplitudes of the E and B fields of the EM wave?

* 48. 15 km from a radio station's transmitting antenna, the amplitude of the electric field is 0.12 V/m. What is the average power output of the radio station?

* 49. The variable capacitance of a radio tuner consists of six plates connected together placed alternately between six other plates, also connected together (Fig. 22–21). Each plate is separated from its neighbor by 1.1 mm of air. One set of plates can move so that the area of overlap varies from $1.0\,\text{cm}^2$ to $9.0\,\text{cm}^2$. (*a*) Are these capacitors connected in series or in parallel? (*b*) Determine the range of capacitance values. (*c*) What value of inductor is needed if the radio is to tune AM stations from 550 kHz to 1600 kHz?

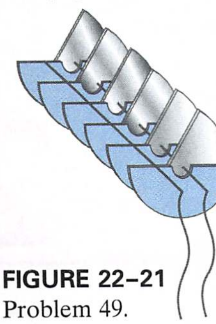

FIGURE 22–21 Problem 49.

* 50. A radio station is allowed to broadcast at an average power not to exceed 25 kW. If an electric field amplitude of 0.020 V/m is considered to be acceptable for receiving the radio transmission, estimate how many kilometers away you might be able to hear this station.

* 51. A point source emits light energy uniformly in all directions at an average rate P_0 with a single frequency f. Show that the peak electric field in the wave is given by

$$E_0 = \sqrt{\frac{\mu_0 c P_0}{2\pi r^2}}.$$

* 52. Suppose a 50-kW radio station emits EM waves uniformly in all directions. (*a*) How much energy per second crosses a 1.0-m^2 area 100 m from the transmitting antenna? (*b*) What is the rms magnitude of the $\vec{\mathbf{E}}$ field at this point, assuming the station is operating at full power? (*c*) What is the voltage induced in a 1.0-m-long vertical car antenna at this distance?

* 53. Repeat Problem 52 for a distance of 100 km from the station.

* 54. What is the maximum power level of the radio station of Problem 52 so as to avoid electrical breakdown of air at a distance of 1.0 m from the antenna? Assume the antenna is a point source. Air breaks down in an electric field of about 3×10^6 V/m. [*Hint*: see Problem 51.]

Answers to Exercises

A: (*a*) 3.8×10^6 Hz; (*b*) 5.5×10^{18} Hz.

B: 45 cm.

C: 3 hours.