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After EM waves were experimentally detected, it became generally accepted that light is an EM wave. 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

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

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.

Radio, TV, cell phone, and other wireless signals are transmitted through space in the radio-wave or microwave part of the EM spectrum.

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. Explain.
2. Is sound an EM wave? If not, what kind of wave is it?
3. Can EM waves travel through a perfect vacuum? Can sound waves? Yes. No.
4. When you flip a light switch on, does the light go on immediately? Explain. No.
5. Are the wavelengths of radio and television signals longer or shorter than those detectable by the human eye? Longer
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 to avoid 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? Radio Micro Infrared
8. Can radio waves have the same frequencies as sound waves (20 Hz–20,000 Hz)? Yes.Lambda=1.5X 10^7 — 10^4 m
9. If a radio transmitter has a vertical antenna, should a receiver's antenna (rod type) be vertical or horizontal to obtain best reception?
10. 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.
11. Discuss how cordless telephones make use of EM waves. What about cell phones?
12. A lost person may signal by switching 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?

MisConceptual Questions

1. In a vacuum, what is the difference between a radio wave and an X-ray?
   (*a*) Wavelength. (*b*) Frequency. (*c*) Speed.
2. The radius of an atom is on the order of 10^{-10} m. In comparison, the wavelength of visible light is
   (*a*) much smaller. (*b*) about the same size. (*c*) much larger.
3. Which of the following travel at the same speed as light? (Choose all that apply.) XXXXX
   (*a*) Radio waves. (*d*) Ultrasonic waves. (*g*) Gamma rays.
   (*b*) Microwaves. (*e*) Infrared radiation. (*h*) X-rays.
   (*c*) Radar. (*f*) Cell phone signals.
4. Which of the following types of electromagnetic radiation travels the fastest?
   (*a*) Radio waves.
   (*b*) Visible light waves.
   (*c*) X-rays.
   (*d*) Gamma rays.
   (*e*) All the above travel at the same speed.
5. In empty space, which quantity is always larger for X-ray radiation than for a radio wave?
   (*a*) Amplitude. (*c*) Frequency.
   (*b*) Wavelength. (*d*) Speed.
6. If electrons in a wire vibrate up and down 1000 times per second, they will create an electromagnetic wave having
   (*a*) a wavelength of 1000 m. (*c*) a speed of 1000 m/s.
   (*b*) a frequency of 1000 Hz. (*d*) an amplitude of 1000 m.
7. If the Earth–Sun distance were doubled, the intensity of radiation from the Sun that reaches the Earth's surface would (*a*) quadruple. (*b*) double. (*c*) drop to $\frac{1}{2}$. (*d*) drop to $\frac{1}{4}$.
8. An electromagnetic wave is traveling straight down toward the center of the Earth. At a certain moment in time the electric field points west. In which direction does the magnetic field point at this moment?
   (*a*) North. (*d*) West. (*g*) Either (*a*) or (*b*).
   (*b*) South. (*e*) Up. (*h*) Either (*c*) or (*d*).
   (*c*) East. (*f*) Down. (*i*) Either (*e*) or (*f*).
9. If the intensity of an electromagnetic wave doubles,
   (*a*) the electric field must also double.
   (*b*) the magnetic field must also double.
   (*c*) both the magnetic field and the electric field must increase by a factor of $\sqrt{2}$.
   (*d*) Any of the above.
10. If all else is the same, for which surface would the radiation pressure from light be the greatest?
    (*a*) A black surface.
    (*b*) A gray surface.
    (*c*) A yellow surface.
    (*d*) A white surface.
    (*e*) All experience the same radiation pressure, because they are exposed to the same light.
11. Starting in 2009, TV stations in the U.S. switched to digital signals. [See Sections 22–7, 17–10, and 17–11.] To watch today's digital broadcast TV, could you use a pre-2009 TV antenna meant for analog? Explain.
    (*a*) No; analog antennas do not receive digital signals.
    (*b*) No; digital signals are broadcast at different frequencies, so you need a different antenna.
    (*c*) Yes; digital signals are broadcast with the same carrier frequencies, so your old antenna will be fine.
    (*d*) No; you cannot receive digital signals through an antenna and need to switch to cable or satellite.

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For assigned homework and other learning materials, go to the MasteringPhysics website.

Problems

22–1 $\vec{B}$ Produced by Changing $\vec{E}$

*1. (II) Determine the rate at which the electric field changes between the round plates of a capacitor, 8.0 cm in diameter, if the plates are spaced 1.1 mm apart and the voltage across them is changing at a rate of 120 V/s.

*2. (II) Calculate the displacement current I_D between the square plates, 5.8 cm on a side, of a capacitor if the electric field is changing at a rate of 1.6×10^6 V/m·s.

*3. (II) At a given instant, a 3.8-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?

*4. (III) A 1500-nF capacitor with circular parallel plates 2.0 cm in diameter is accumulating charge at the rate of 32.0 mC/s at some instant in time. What will be the induced magnetic field strength 10.0 cm radially outward from the center of the plates? What will be the value of the field strength after the capacitor is fully charged?

22–2 EM Waves

5. (I) If the electric field in an EM wave has a peak magnitude of 0.72×10^{-4} V/m, what is the peak magnitude of the magnetic field strength?

6. (I) If the magnetic field in a traveling EM wave has a peak magnitude of 10.5 nT, what is the peak magnitude of the electric field?

7. (I) In an EM wave traveling west, the B field oscillates up and down vertically and has a frequency of 90.0 kHz and an rms strength of 7.75×10^{-9} T. Determine the frequency and rms strength of the electric field. What is the direction of its oscillations?

8. (I) How long does it take light to reach us from the Sun, 1.50×10^8 km away? 0.5 X 10^3 sec

9. (II) How long should it take the voices of astronauts on the Moon to reach the Earth? Explain in detail. d=3.6 X 10^5 km 1.2 sec

22–3 Electromagnetic Spectrum

10. (I) An EM wave has a wavelength of 720 nm. What is its frequency, and how would we classify it? 4.2X10^14 Hz; IR

11. (I) An EM wave has frequency 7.14×10^{14} Hz. What is its wavelength, and how would we classify it? 4.2X10^(-7) m Blue

12. (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? 6X10^6Hz

13. (I) What is the frequency of a microwave whose wavelength is 1.50 cm? 2X10^10Hz

14. (II) Electromagnetic waves and sound waves can have the same frequency. (*a*) What is the wavelength of a 1.00-kHz electromagnetic wave? (*b*) What is the wavelength of a 1.00-kHz sound wave? (The speed of sound in air is 341 m/s.) (*c*) Can you hear a 1.00-kHz electromagnetic wave? 3X10^5m .341 m No

15. (II) (*a*) What is the wavelength of a 22.75×10^9 Hz radar signal? (*b*) What is the frequency of an X-ray with wavelength 0.12 nm? 1.3X10^-2m 2.5X10^18Hz

16. (II) How long would it take a message sent as radio waves from Earth to reach Mars when Mars is (*a*) nearest Earth, (*b*) farthest from Earth? Assume that Mars and Earth are in the same plane and that their orbits around the Sun are circles (Mars is $\approx 230 \times 10^6$ km from the Sun). 267s 1267s

17. (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? 3.97X10^16 m

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

19. (II) Pulsed lasers used for science and medicine produce very brief bursts of electromagnetic energy. If the laser light wavelength is 1062 nm (Neodymium–YAG laser), and the pulse lasts for 34 picoseconds, how many wavelengths are found within the laser pulse? How brief would the pulse need to be to fit only one wavelength? 9.5X10^15m

22–4 Measuring the Speed of Light

20. (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 (1/8 of a revolution, Fig. 22–10)?

21. (II) A student wants to scale down Michelson's light-speed experiment to a size that will fit in one room. An eight-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?

22–5 Energy in EM Wave

22. (I) The $\vec{E}$ field in an EM wave has a peak of 22.5 mV/m. What is the average rate at which this wave carries energy across unit area per unit time?

23. (II) The magnetic field in a traveling EM wave has an rms strength of 22.5 nT. How long does it take to deliver 365 J of energy to 1.00 cm^2 of a wall that it hits perpendicularly?

24. (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 30.8 mV/m?

25. (II) A spherically spreading EM wave comes from an 1800-W source. At a distance of 5.0 m, what is the intensity, and what is the rms value of the electric field?

26. (II) If the amplitude of the B field of an EM wave is 2.2×10^{-7} T, (*a*) what is the amplitude of the E field? (*b*) What is the average power transported across unit area by the EM wave?

27. (II) What is the average energy contained in a 1.00-m^3 volume near the Earth's surface due to radiant energy from the Sun? See Example 22–4.

28. (II) A 15.8-mW laser puts out a narrow beam 2.40 mm in diameter. What are the rms values of E and B in the beam?

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

30. (II) A high-energy pulsed laser emits a 1.0-ns-long pulse of average power 1.5×10^{11} W. The beam is nearly a cylinder 2.2×10^{-3} m in radius. Determine (*a*) the energy delivered in each pulse, and (*b*) the rms value of the electric field.

8) $c = \dfrac{d}{t}$, so $t = \dfrac{d}{c} = \dfrac{1.5 \times 10^{11}}{3 \times 10^{8}} = 5 \times 10^{2}\,\text{s}$.

9) $d = 3.6 \times 10^{8}\,\text{m}$, so $t = \dfrac{3.6 \times 10^{8}}{3 \times 10^{8}} = 1.2\,\text{s}$.

10) $c = \lambda f$, so $f = \dfrac{c}{\lambda} = \dfrac{3 \times 10^{8}}{7.2 \times 10^{-8}} = 4.2 \times 10^{14}\,\text{Hz}$.

11) $\lambda = \dfrac{c}{f} = \dfrac{3 \times 10^{8}}{7.14 \times 10^{14}} = 4.2 \times 10^{-7}\,\text{m}$.

12) $f = \dfrac{c}{\lambda} = \dfrac{3 \times 10^{8}}{49} = 6 \times 10^{6}\,\text{Hz}$.

13) $f = \dfrac{c}{\lambda} = \dfrac{3 \times 10^{8}}{1.5 \times 10^{-2}} = 2 \times 10^{10}\,\text{Hz}$.

14) $\lambda = \dfrac{c}{f} = \dfrac{3 \times 10^{8}}{10^{3}} = 3 \times 10^{5}\,\text{m}$.

$\lambda = \dfrac{v}{f} = \dfrac{341}{10^{3}} = 3.41 \times 10^{-1}\,\text{m}$.

15) $\lambda = \dfrac{c}{f} = \dfrac{3 \times 10^{8}}{22.75 \times 10^{9}} = 1.3 \times 10^{-2}\,\text{m}$.

$f = \dfrac{c}{\lambda} = \dfrac{3 \times 10^{8}}{0.12 \times 10^{-9}} = 2.5 \times 10^{18}\,\text{Hz}$.

16) Radius of earth orbit: $1.5 \times 10^{11}\,\text{m}$.

Radius of Mars orbit: $2.3 \times 10^{11}\,\text{m}$.

Closest distance, d_c, is the difference of these.

Furthest distance, d_f, is the sum.

$t_\text{c} = \dfrac{0.8 \times 10^{11}}{3 \times 10^{8}} = 2.67 \times 10^{2}\,\text{s}$.

$t_\text{f} = \dfrac{3.8 \times 10^{11}}{3 \times 10^{8}} = 1.267 \times 10^{3}\,\text{s}$.

17) Seconds/year: $60 \times 60 \times 24 \times 365 = 3.15 \times 10^{7}$.

$d = (3 \times 10^{8})(4.2 \times 3.15 \times 10^{7}) = 3.97 \times 10^{16}\,\text{m}$.

18) $d = (3 \times 10^{8})(3.15 \times 10^{7}) = 9.5 \times 10^{15}\,\text{m}$.