CHAPTER  24 | ELECTROMAGNETIC WAVES

CONCEPTUAL QUESTIONS

1. **REASONING AND SOLUTION**  
   a. The intensity of a wave refers to the power $P$ carried by the wave that passes perpendicularly through a surface in the path of the wave, divided by the area $A$ of the surface. It is given for sound waves by Equation 16.8 and for electromagnetic waves by Equation 24.4. The concept of intensity applies to both sound waves and electromagnetic waves, because both types of wave transfer energy and, therefore, power away from their respective sources.

   b. In a transverse wave, the particles of the medium vibrate perpendicular to the direction of propagation of the wave. In the case of electromagnetic waves, there are no particle vibrations, but rather the electric and magnetic fields oscillate perpendicular to the direction of propagation of the wave. When a wave is produced or altered so that the vibrations or oscillations take place in a particular direction perpendicular to the wave velocity, the wave is said to be polarized.

   In a longitudinal wave, the notion of polarization has no meaning, as discussed in Section 24.6 of the text. Therefore, **transverse waves can be polarized**, while **longitudinal waves cannot be polarized**.

   Since sound waves are longitudinal waves, while electromagnetic waves are transverse waves, the concept of polarization applies only to electromagnetic waves.

2. **REASONING AND SOLUTION**  Refer to Figure 24.2. Between the times indicated in parts $c$ and $d$ in the drawing, negative charges have moved to the top of the antenna, leaving a net positive charge of equal magnitude on the bottom of the antenna. Therefore, as the negative charges flow, the conventional current points toward the bottom of the antenna. Using RHR-2, the magnetic field for the electromagnetic wave at $P$ must point out of the page.

3. **REASONING AND SOLUTION**  A transmitting antenna is located at the origin of an $x$, $y$, $z$ axis system, and broadcasts an electromagnetic wave whose electric field oscillates along the $y$ axis. The wave travels along the $+x$ axis. Three possible loops can be used with an LC-tuned circuit to detect the wave: One loop lies in the $x$, $y$ plane, another in the $x$, $z$ plane, and the third in the $y$, $z$ plane.

   The loop that will detect the electromagnetic wave must be oriented so that the normal to the loop is parallel to the magnetic field. Then, as the wave passes by the loop, the changing magnetic field penetrates the loop and results in an induced emf and current, as predicted by Faraday's law. Since the electromagnetic wave travels along the $+x$ direction, and the electric field oscillations of the electromagnetic wave are along the $y$ axis, the magnetic field oscillations will be along the $z$ axis. For optimum reception, therefore, the loop should lie in the $x$, $y$ plane so that the normal to the loop is in the $z$ direction.
4. **REASONING AND SOLUTION** When a straight-wire antenna is used as the receiving antenna to detect electromagnetic waves, the wires must be oriented parallel to the electric field, as shown in Figure 24.5. The electric field exerts a force on the electrons in the wire and causes them to oscillate up and down along the length of the antenna. Since the electric field drives the electrons directly, the peak emf that causes the ac current in the receiving antenna depends on the amplitude of the electric field. It does not depend on the frequency of the wave.

When a loop antenna such as that shown in Figure 24.6, is used as the receiving antenna, the induced emf around the loop depends on the rate at which the magnetic flux changes with time, $\frac{\Delta \Phi}{\Delta t}$. If $B$ represents the instantaneous magnitude of the magnetic field and $A$ represents the cross-sectional area of the loop, and the normal of the loop points in the same direction as $B$, then $\Phi = BA$. Then $\frac{\Delta \Phi}{\Delta t} = \frac{\Delta (BA)}{\Delta t}$. Since the area of the loop, $A$, does not change, it follows that $\frac{\Delta \Phi}{\Delta t} = \frac{\Delta B}{\Delta t}A$. Hence, the induced emf in the receiving loop depends on the rate at which the magnetic field of the wave changes with time, and therefore, on the frequency of the electromagnetic wave. Thus, the peak value of the emf induced in a loop antenna depends on the frequency of the wave.

5. **REASONING AND SOLUTION** The electric field of an electromagnetic wave is related to the magnetic field through the relation $E = cB$ (Equation 24.3). Therefore, if the electric field of a wave decreases in magnitude, the magnetic field must also decrease.

This conclusion can also be reached by considering the fact that in an electromagnetic wave propagating through air or vacuum, the electric field and the magnetic field carry equal amounts of energy per unit volume of space. If the electric field of a wave decreases in magnitude, the electric energy per unit volume must decrease. The magnetic energy per unit volume must decrease to the same amount; therefore, the magnitude of the associated magnetic field must also decrease.

6. **REASONING AND SOLUTION** The same Doppler effect arises for electromagnetic waves when either the source or the observer of the waves moves; it is only the relative motion of the source and the observer with respect to one another that is important (see Section 24.5). Therefore, when an astronomer measures the Doppler change in frequency for the light reaching earth from a distant star, the astronomer cannot tell whether the star is moving away from the earth or whether the earth is moving away from the star.

7. **REASONING AND SOLUTION** The only real difference between a polarizer and an analyzer is the purpose for which they are used. Both consist of a piece of polarizing material. When the piece of polarizing material is used to produce a desired polarization direction, it is referred to as a polarizer. When the piece of polarizing material is used to change the polarization direction and to adjust the intensity so that the polarization direction of the incident light can be determined, it is referred to as an analyzer. The same piece of polarizing material can be used as the polarizer in one situation and the analyzer in another.

8. **REASONING AND SOLUTION** Malus' law applies to the setup in Figure 24.20, which shows the analyzer rotated through an angle $\theta$ and the polarizer held fixed. When the analyzer is held fixed and the polarizer is rotated, Malus' law still applies. Malus' law states that the average intensity $\bar{S}$
depends on the angle $\theta$ between the polarizer and analyzer. It does not matter whether the polarizer is fixed and the analyzer is rotated, or vice-versa.

9. **REASONING AND SOLUTION** In Example 7, we saw that, when the angle between the polarizer and analyzer is $63.4^\circ$, the intensity of the transmitted light drops to one-tenth of that of the incident unpolarized light. The light intensity that is not transmitted is absorbed by both the polarizer and the analyzer. The polarizer absorbs one-half of the incident intensity. The analyzer absorbs four-tenths, or two-fifths, of the original incident light. This absorbed energy results in an increase in the temperature of the polarizer and analyzer.

10. **REASONING AND SOLUTION** Light is incident from the left on two pieces of polarizing material, 1 and 2. As part $a$ of the following drawing illustrates, the transmission axis of material 1 is along the vertical direction, while that of material 2 makes an angle of $\theta$ with respect to the vertical. In part $(b)$ of the drawing, the two polarizing materials are interchanged.

\[\begin{array}{c|c}
\text{Incident light} & \text{Transmitted light} \\
\hline
\text{#1} & \theta \\
\hline
\text{#2} & \text{Transmitted light} \\
\end{array}\]

(a)

\[\begin{array}{c|c}
\text{Incident light} & \text{Transmitted light} \\
\hline
\theta & \\
\hline
\text{#2} & \text{#1} \\
\end{array}\]

(b)

a. If the incident light is unpolarized and has an average intensity $\bar{I}$, then the average intensity of the light that leaves polarizer #1 and strikes polarizer #2 in Figure $(a)$ is $\bar{S}_0 = \bar{I}/2$. According to Malus' law, the average intensity of the light leaving polarizer #2 is $\bar{S} = \bar{S}_0 \cos^2 \theta = (\bar{I} \cos^2 \theta)/2$.

Similarly, the average intensity of the light that leaves polarizer #2 and strikes polarizer #1 in Figure $(b)$ is $\bar{S}_0 = \bar{I}/2$. The angle between the transmission axis of polarizer #2 and polarizer #1 is still $\theta$, so that the average intensity of the light leaving polarizer #1 in $(b)$ is $\bar{S} = \bar{S}_0 \cos^2 \theta = (\bar{I} \cos^2 \theta)/2$. Therefore, the transmitted light in Figure $(a)$ is the same as that in Figure $(b)$.

b. If the incident light in Figure $(a)$ is polarized along the vertical direction with average intensity $\bar{I}$, then, since the polarization direction of the light is the same as the transmission axis of the polarizer, all of the incident light is transmitted. The average intensity of the light that leaves polarizer #1 and strikes polarizer #2 is $\bar{S}_0 = \bar{I}$. According to Malus' law, the average intensity of the light leaving polarizer #2 is $\bar{S} = \bar{S}_0 \cos^2 \theta = \bar{I} \cos^2 \theta$.

In Figure $(b)$ we have from Malus’ law that the average intensity of the light that leaves polarizer #2 and strikes polarizer #1 is $\bar{S}_0 = \bar{I} \cos^2 \theta$. The angle between the transmission axis of polarizer #2 and polarizer #1 in Figure $(b)$ is $\theta$. Therefore, according to Malus' law, the average intensity of the light leaving polarizer #1 in Figure $(b)$ is $\bar{S} = \bar{S}_0 \cos^2 \theta = (\bar{I} \cos^2 \theta) \cos^2 \theta = \bar{I} \cos^4 \theta$. Therefore,
the intensity of the transmitted light in Figure (a) is greater than the intensity of the transmitted light in Figure (b).

11. **REASONING AND SOLUTION**  
Light from the sun is unpolarized; however, when the sunlight is reflected from horizontal surfaces such as the surface of a swimming pool, lake, or ocean, the reflected light is partially polarized in the horizontal direction. Polaroid sunglasses are constructed with lenses made of Polaroid (a polarizing material) with the transmission axis oriented vertically. Thus, the horizontally polarized light that is reflected from horizontal surfaces is blocked from the eyes.

Suppose you are sitting on the beach near a lake on a sunny day, wearing Polaroid sunglasses. When you are sitting upright, the horizontally polarized light that is reflected from the lake is blocked from your eyes, as discussed above. When you lay down on your side, facing the lake, the transmission axis of the Polaroid sunglasses is now oriented in a nearly horizontal direction. Most of the horizontally polarized light that is reflected from the lake is transmitted through the sunglasses and reaches your eyes. Therefore, the sunglasses don't work as well as they did when you were sitting in an upright position.