Answer to Essential Question 22.4: If the truck travels away, the frequency shifts lower instead of higher. The difference when we apply Equation 22.6 is that we use a minus sign instead of a plus sign. None of the numbers change, so the frequency shift still has a magnitude of 1600 Hz.

22-5 Polarized Light

Polarizing film consists of linear molecules aligned with one another. When an electromagnetic wave is incident on the film, electric field components that are parallel to the molecules cause electrons to oscillate back and forth along the molecules. This transfers energy from the wave to the molecules, so that part of the wave is absorbed by the film. Waves with electric field vectors in a direction perpendicular to the molecules do not transfer energy to the molecules, however, so they pass through the polarizing film without being absorbed. An electromagnetic wave emerges from the polarizing film **linearly polarized** – all its electric field vectors are aligned with the transmission axis of the polarizing film (which we call a polarizer), the transmission axis being perpendicular to the long molecules in the film.

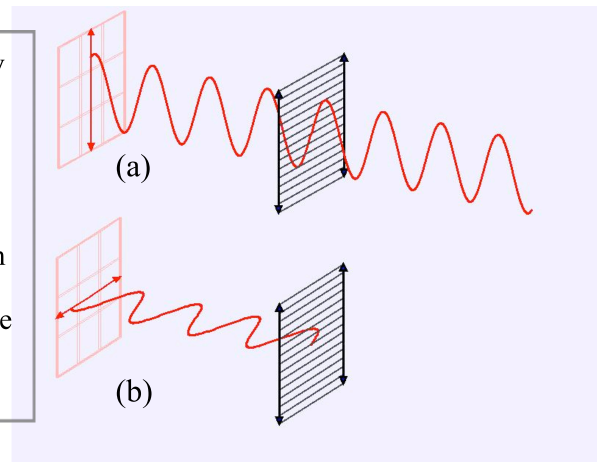

Figure 22.5: A schematic view of what happens to a linearly polarized electromagnetic wave that is incident on a polarizer. The arrow at left shows the polarization direction of the wave, while the vertical arrows on the polarizer indicate the transmission axis for the polarizer. The horizontal lines on the polarizer show the orientation of the long molecules in the polarizer. (a) The wave passes through the polarizer, because the polarization direction matches the transmission axis. (b) The wave is completely blocked by the polarizer, because the polarization direction of the polarizer is perpendicular to the polarizer's transmission axis.

Figure 22.5 shows two special cases, in which the wave is linearly polarized with its electric field vectors either parallel to, or perpendicular to, the polarizer's transmission axis. Figure 22.6 shows the more general case in which the electric field vectors make an angle $\Delta\theta$ with the transmission axis. Splitting the electric field vectors into components parallel to and perpendicular to the transmission axis, the parallel component is transmitted while the perpendicular component is entirely absorbed by the polarizer.

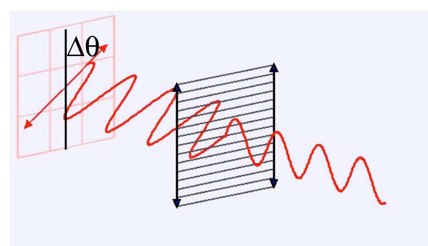

Figure 22.6: The general case of a linearly polarized wave that is incident on a polarizer.

The light emerging from the polarizer has two important features:

- it is linearly polarized, with the polarization direction of the wave matching the transmission axis of the polarizer it just passed through, and
- the intensity of the wave is reduced, because energy is absorbed by the polarizer.

If the magnitude of the electric field in the incident wave is E_0, the magnitude of the electric field in the wave emerging from the polarizer is $E_1 = E_0 \cos(\Delta\theta)$, because it is the cosine component in Figure 22.6 that is transmitted by the polarizer. In general, a wave is characterized by its intensity, which is proportional to the square of the amplitude of the electric fields. Thus,

$I_1 = I_0 \cos^2(\Delta\theta)$. (Eq. 22.7: **Malus' Law for the intensity of light emerging from a polarizer**)

Malus' Law applies when the incident light is linearly polarized. Figure 22.7 shows unpolarized light incident on a polarizer. On average, half the energy is associated with waves in which the electric field vectors are parallel to the polarizer's transmission axis, which are 100% transmitted by the polarizer, while the other half of the energy is associated with waves in which the electric field vectors are perpendicular to the transmission axis, which are 100% absorbed. Thus, the beam emerging from the polarizer is half as intense as that of the incident light. As with a linearly polarized incident wave, the wave emerging from the polarizer is linearly polarized in the direction of the polarizer's transmission axis.

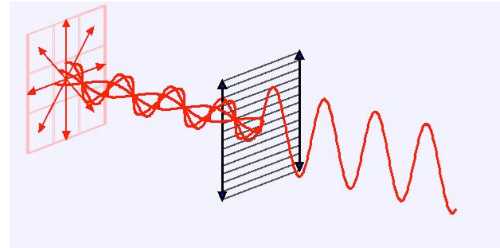

Figure 22.7: When unpolarized light is incident on a polarizer, the emerging beam is (i) half as intense as the incident beam, and (ii) linearly polarized in a direction parallel to the polarizer's transmission axis.

EXAMPLE 22.5 – A sequence of polarizers
As shown in Figure 22.8, light with its polarization direction at 30° to the vertical passes through a sequence of three polarizers. The light has an intensity of 800 W/m². Measured from the vertical, the transmission axes of the polarizers are at angles of 0°, 30°, and 75°, respectively. What is the intensity of the light when it emerges from (a) the first polarizer, (b) the second polarizer, and (c) the third polarizer?

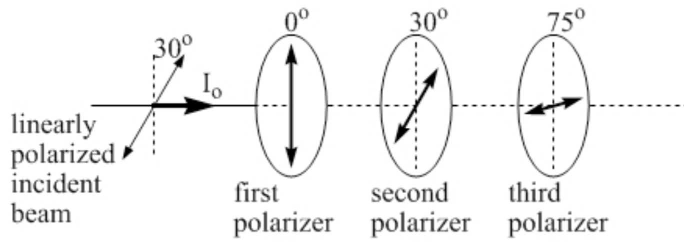

Figure 22.8: Linearly polarized light passes through a sequence of three polarizers, for Example 22.5.

SOLUTION

(a) Because the light is linearly polarized to begin with, we apply Malus' Law. In this case, the angle between the polarization direction of the light and the transmission axis of the polarizer the light is incident on is $\Delta\theta_1 = 30° - 0° = 30°$. Applying Malus' Law gives:

$$I_1 = I_0 \cos^2(\Delta\theta_1) = (800 \text{ W/m}^2)\cos^2(30°) = (800 \text{ W/m}^2) \times \frac{3}{4} = 600 \text{ W/m}^2 .$$

(b) When the light emerges from the first polarizer, it is polarized at an angle of 0° to the vertical, matching the orientation of the transmission axis of the polarizer it just passed through. With the second polarizer at 30°, the angle between the light and the transmission axis is $\Delta\theta_2 = 30° - 0° = 30°$. Applying Malus' Law gives:

$$I_2 = I_1 \cos^2(\Delta\theta_2) = (600 \text{ W/m}^2)\cos^2(30°) = (600 \text{ W/m}^2) \times \frac{3}{4} = 450 \text{ W/m}^2 .$$

(c) When the light emerges from the second polarizer, it is once again polarized at an angle of 30° to the vertical, matching the orientation of the transmission axis of the polarizer it just passed through. With the third polarizer at 75°, the angle between the light and the transmission axis is $\Delta\theta_3 = 75° - 30° = 45°$. Applying Malus' Law gives:

$$I_3 = I_2 \cos^2(\Delta\theta_3) = (450 \text{ W/m}^2)\cos^2(45°) = (450 \text{ W/m}^2) \times \frac{1}{2} = 225 \text{ W/m}^2 .$$

Related End-of-Chapter Exercises: 6 – 12.

Essential Question 22.5: Crossed polarizers are two polarizers with transmission axes that are perpendicular to one another. What is the final intensity (a) if unpolarized light with an intensity of 600 W/m² is incident on crossed polarizers, and (b) if a third polarizer, with a transmission axis at 45° to the first polarizer, is placed between the original two polarizers?