10.5 Polarization of Light

Electromagnetic waves have electric and magnetic fields that are perpendicular to each other and to the direction of propagation. These fields can take many different directions and still be perpendicular to the direction of propagation. When you describe an electromagnetic wave, you need to include the direction of the electric field, as well as the amplitude, frequency, wavelength, and direction of propagation. These directions determine the polarization of the light, which is the subject of this section.

What Is Polarized Light?

polarized light light waves that vibrate in a single plane

unpolarized light light waves that vibrate in many different planes

polarizer a device that allows only light with an electric field along a single direction to pass through

A variety of sources are capable of producing electromagnetic radiation. Examples are the Sun, a microwave oven, an X-ray machine, a radio transmitter, and a light bulb. Each source produces electromagnetic waves that transmit energy. The polarization of electromagnetic waves describes the way in which the electric field is oriented relative to the direction of propagation. The light waves in **polarized light** vibrate in a single plane. A mixture of light with different waves and different directions of propagation is **unpolarized light**. In other words, a source of light creates oscillating electric and magnetic fields, perpendicular to each other, that move away from the source. Light can also be a mixture of polarized and unpolarized light, called partially polarized light. Polarization occurs when you block one of the axes of light oscillation with a polarizer (**Figure 1**). A **polarizer** is a filter or device that allows only light with an electric field along one direction to pass through. If you do not block any of the axes, then the light remains unpolarized.

Many applications make use of the polarization of electromagnetic waves. For example, sunglasses use filters to block glare reflected from horizontal surfaces such as the surface of a lake. Materials such as glass and plastic have different indices of refraction for different polarizations of light. The plastic instruments in **Figure 2** produce a colourful display when viewed through polarized sunglasses. This effect has practical uses in analyzing stresses to identify where structural failure might occur.

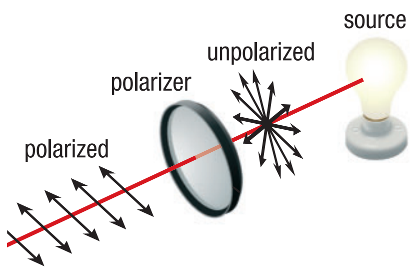

Figure 1 In this example, only light that vibrates in the horizontal plane passes through the polarizing filter. This light is said to be polarized along the horizontal direction.

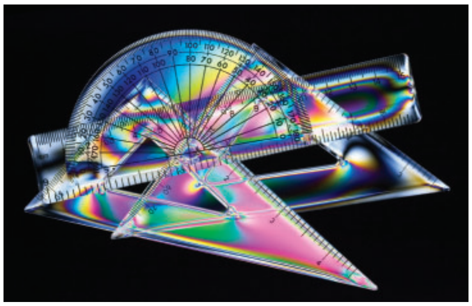

Figure 2 Areas of weakness within these plastic geometry instruments are visible under polarized light.

Generating Waves with Specific Polarizations

linearly polarized (plane polarized) the quality of light waves that are polarized in one direction, perpendicular to the direction of propagation

Radio stations can generate waves with specific polarizations by using various antenna configurations. Light that is entirely polarized in one direction that is perpendicular to the direction of propagation is said to be **linearly polarized**, or **plane polarized**.

Many natural phenomena, such as reflection, change unpolarized light to partially polarized light. The amount of light reflecting from a surface for each angle of incidence typically depends on whether the electric field of the light is along the surface or perpendicular to the surface. That is why light reflecting from road and water surfaces is typically partially polarized. Light from the Sun encounters small particles that scatter the waves. Shorter wavelengths are scattered more than longer wavelengths, which is why the sky appears blue. As a result, the sky often appears more vivid when viewed through a pair of polarized sunglasses (**Figure 3**). The degree of polarization depends on the relative orientation of the viewer, the source of the light, and the direction of the sky being viewed.

Figure 3 The colours in the image on the right are much more vivid because the photo was taken through a polarized filter.

Polarization by Selective Absorption

Ordinary, unpolarized light can act as a source of polarized light if you pass it through a polarizer. The direction of the electric field that the polarizer allows through is the **transmission axis** of the polarizer (**Figure 4**). Light that leaves the polarizer is always linearly polarized along the direction of the axis of the polarizer.

transmission axis the direction of the electric field that a polarizer allows through

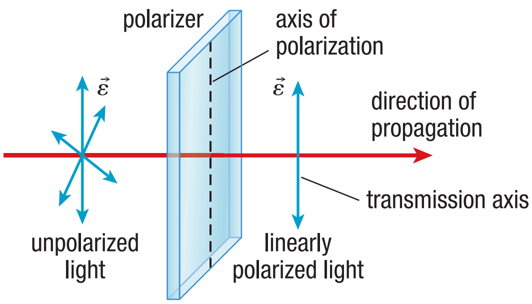

Figure 4 The polarizer allows light to pass through and become linearly polarized.

One example of a polarizer, called Polaroid, consists of a type of film used in instant cameras to generate developed film images. Polaroid film is a plastic sheet. It absorbs light when the electric field is perpendicular to the transmission axis and transmits light when the electric field is parallel to the axis of the polarizer. Polaroid film contains molecules (usually polyvinyl alcohol dyed with iodine) that selectively absorb light whose oscillating electric field is along the direction of the molecules. Light with an electric field that is perpendicular to the direction of the molecules passes through. The result is that the light passing through the film is linearly polarized, making detecting polarized light in nature easy.

How can you determine the strength, or intensity, of light passing through a polarizer? Recall that intensity is related to wavelength—the shorter the wavelength of light, the greater is its intensity. Consider what happens when the incident light is at an angle θ with respect to the polarization axis of the polarizer. The component of the electric field that is parallel to the polarizer is given by $\varepsilon_{in} \cos \theta$. The intensity, I, of the light is proportional to the square of the magnitude of its electric field vector. So, the transmitted intensity is related to the incident intensity by a relation called **Malus's law**:

Malus's Law

$$I_{out} = I_{in} \cos^2 \theta$$

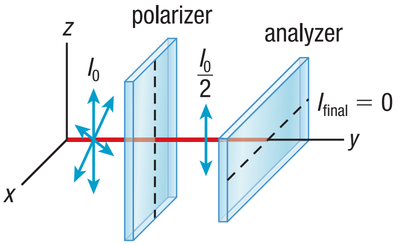

Figure 5 Light that is transmitted through the first polarizer passes through a second polarizer, called an analyzer, to verify that the light has indeed been polarized.

analyzer a second polarizer used to verify that the light from the first polarizer is polarized

The SI unit for intensity is the candela. To determine the proportion of unpolarized light that passes through a polarizer, you calculate average intensity using Malus's law over all possible incident polarization directions. As you might expect, only half the light passes through the polarizer:

$$I_{\text{out}} = \frac{1}{2} I_{\text{in}}$$

If you wanted to verify that the light from the first polarizer is indeed polarized, you could pass it through a second polarizer, called an **analyzer** (**Figure 5**). When the analyzer in Figure 5 is oriented at 90° to the polarizer, no light passes through. As the analyzer is rotated through 90° in either direction, the light intensity increases to its maximum value. The variation of intensity with rotation of an analyzer indicates the state of polarization of the light reaching it. You can use a similar arrangement to observe how some materials rotate the direction of polarization by observing the analyzer to determine the minimum transmission when the sample is between the polarizer and the analyzer.

Mini **Investigation**

Observing Polarization from Reflection

Skills: Performing, Observing, Analyzing, Communicating

SKILLS HANDBOOK A2.1

Light from the Sun and from most artificial light sources is unpolarized. Many familiar processes such as reflection can polarize light. In this activity, you will examine how a polarizer and analyzer work using Polaroid filters, and you will examine polarization effects in reflection.

Equipment and Materials: bright source of light; 2 Polaroid filters

1. Hold a Polaroid filter up to the light. Record your observations.

To unplug the lamp, pull on the plug, not the cord. Do not touch the lamp because it will be hot after use. Never look directly at the light source. Never look directly at the Sun, even through the Polaroid filter.

2. Hold two Polaroid filters up to the light, one above the other. Keeping one fixed, rotate the other 180°. Record your observations.
3. Create a glare on a surface using the light source. Observe the glare through a single Polaroid filter. Record your observations.
4. Hold the Polaroid filter against various regions of a clear sky away from the Sun. Rotate the filter.

A. Describe the effects of rotating the second filter. What happens to the light? T/I C

B. Explain why glare on a surface is reduced when you use a Polaroid filter. T/I C

C. Explain the variations in light seen by changing the location of a Polaroid filter against various regions of the sky. T/I C

Polarization by Reflection

In **Figure 6**, on the next page, an unpolarized light wave strikes the flat surface of a non-metallic material at an angle of less than 90° (not normal to the surface). Upon impact, the light's oscillating electric fields vibrate within the surface of the material. This, in turn, produces new outgoing light waves. Some of these new waves reflect from the surface and some refract into the material. The following discussion analyzes the mechanics of these interactions.

Like all electromagnetic waves, the electric field of the incoming light waves oscillates in all directions that are perpendicular to the direction of propagation. Thus, some of the electric field oscillates parallel to the surface of the material. Most of it oscillates in directions that are partially parallel and partially perpendicular to the surface. Light waves that penetrate the surface of the material transfer their energy to some of the electrons within the material. This, in turn, causes those electrons to begin to oscillate, which in turn produces electromagnetic, or light, waves. Some of these waves vibrate parallel to the surface, which means that these waves also vibrate perpendicular to the direction of reflection. These light waves encounter no obstacles when radiating in that direction and are free to produce a reflected wave.

However, light waves that vibrate partially perpendicular to the surface do not vibrate completely perpendicular to the direction of reflection. Since an electric field must oscillate perpendicular to the direction of reflection to propagate a wave in that direction, these light waves cannot radiate as effectively. The result is that some of the light from these waves propagates in the reflection direction, and some of it refracts into the material. The overall effect is that the light reflecting from the surface is partially polarized along the direction parallel to the surface. The relative intensity of the reflected waves depends on the angle of incidence, so the degree of polarization of the reflected light depends on the angle of incidence.

At some particular angle of incidence, called **Brewster's angle**, the direction of the reflected portion of the wave is perpendicular to the direction of the refracted portion of the wave (Figure 6). Maximum polarization of the reflected light occurs at Brewster's angle. You can calculate this angle using **Brewster's law**, which states that the tangent of Brewster's angle equals the ratio of the indices of refraction:

Brewster's Law

$$\tan \theta_B = \frac{n_2}{n_1}$$

At this angle, part of the electric field of the incident light oscillates along the direction of reflection. The photons that penetrate the material cannot radiate in this direction, so that portion of the incident light is not reflected at all. Meanwhile, the part of the light that oscillates parallel to the surface keeps reflecting. Thus, at an angle of incidence equal to Brewster's angle, the reflected light is 100 % polarized.

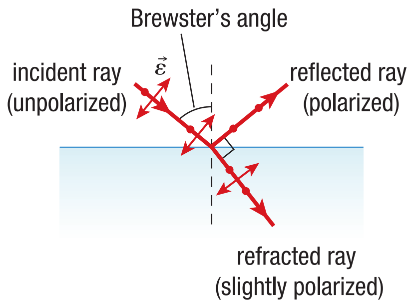

Figure 6 At Brewster's angle, the law of reflection and Snell's law of refraction require that the direction of the reflected ray is perpendicular to the direction of the refracted ray. Light waves that vibrate into the surface instead of along it, in response to the electric fields for incident polarization, cannot radiate in the reflected direction. Note that the red dots represent electric field lines that are perpendicular to the page.

Brewster's angle the angle at which the direction of the reflected portion of the wave is perpendicular to the direction of the refracted portion of the wave

Polarization by Scattering

Figure 7 shows that sunlight, which is unpolarized, can become polarized by **scattering**, that is, after it is scattered, or dispersed, after collisions between molecules in the atmosphere. Figure 7(a) shows an unpolarized wave of sunlight approaching a molecule in the atmosphere. When the wave hits the molecule, energy is transferred from the light wave to the molecule. This causes the positive and negative charges within the molecule to oscillate. Figures 7(b) and 7(c) show this motion for light polarized in two different directions. In Figure 7(b), the direction of polarization and the direction of the electric fields are vertical. Therefore, the molecular charges vibrate up and down and produce new outgoing waves that are also polarized vertically. These outgoing waves are called scattered waves. Figure 7(c) shows how the molecular charges move when the incoming light is polarized horizontally. The charges now oscillate in a horizontal direction and again produce scattered light waves. Since vibrating charges do not radiate light waves in the direction that the charges move, no scattered light reaches the observer looking along the vibration direction. Now combine the results in Figures 7(b) and 7(c) to understand how unpolarized sunlight is scattered. The part of this light that is polarized vertically scatters to the observer, but none of the horizontally polarized scattered light propagates in the observer's direction. Hence, the light that reaches the observer is said to be polarized by scattering.

scattering the change in direction of light waves as a result of collisions

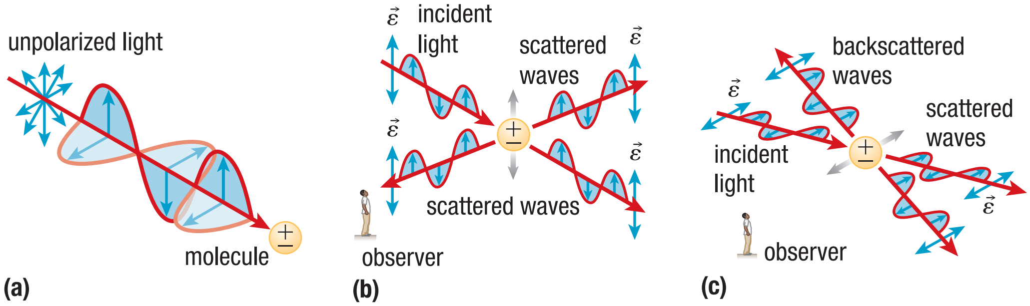

Figure 7 (a) Light from the Sun is unpolarized. (b) Light becomes polarized after scattering. (c) Different polarizations are scattered differently, which affects what an observer sees.

Optical Activity and Liquid Crystal Displays

optical activity the rotation of the direction of polarization when linearly polarized light interacts with certain molecules

liquid crystal display (LCD) a thin, flat display that makes use of polarizers and optical activity

When linearly polarized light passes through certain materials, the materials rotate the direction of the light's polarization (**Figure 8**) in an effect called **optical activity**. Materials that are optically active usually contain molecules with a screw-like or helical structure. Simple sugars, such as fructose and sucrose, are examples of optically active molecules. The thin, flat displays on wristwatches, cellphones, and many other devices, called **liquid crystal displays (LCDs)**, make use of polarizers to create optical activity. **Figure 9** shows how LCDs work. A polarizer linearly polarizes the incident light (Figure 9(a)). The polarized light then passes through a film that contains the optically active liquid crystal. The long, screw-shaped molecules in the liquid crystal rotate the plane of polarization by 90° so that the outgoing light can pass through an output polarizer. To turn off the display, a circuit applies a voltage to the liquid crystal, aligning the molecules in such a way that they no longer rotate the direction of polarization (Figure 9(b)). The light that comes out of the liquid crystal is then polarized at 90° relative to the output polarizer, so no light is transmitted and the display appears dark.

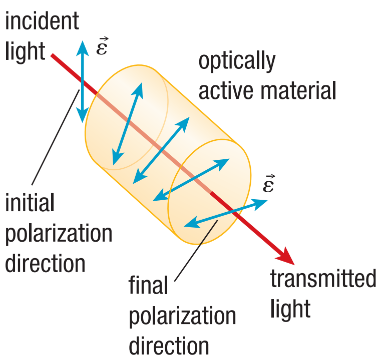

Figure 8 Polarized light passes through an optically active material, and the material changes the direction of polarization.

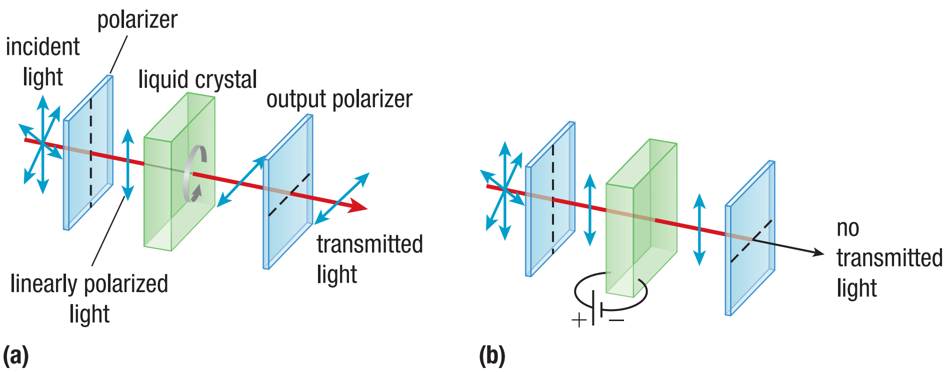

Figure 9 (a) When no voltage is applied, the liquid crystal linearly polarizes the light. (b) An applied voltage causes the liquid crystal to stop rotating its plane of polarization.

By applying different voltages to different areas of the liquid crystal, an LCD device can form various patterns of light and dark regions corresponding to letters or numbers. This is how the display of a wristwatch, a cellphone, and an MP3 player, as well as other similar displays, form the letters and numbers that you see. You can tell that the light from an LCD screen is polarized by placing a polarizer like your sunglasses in front of the screen.

Research This

Holography

Skills: Researching, Analyzing, Evaluating, Communicating — SKILLS HANDBOOK A4.1

You may have seen a three-dimensional image produced by holography, which uses interference effects to reconstruct an image (**Figure 10**). Holography has many potential uses, and some newer techniques under development use polarization holography.

1. Research holography on the Internet.

A. What is holography, and how does it work? K/U

B. What equipment is needed to make a hologram? K/U

C. How does polarization affect holography? K/U

D. List two everyday applications of holography and two novel applications of this technology. K/U

E. Prepare a short presentation summarizing the results of your research. K/U C

Figure 10 This holographic image of a dinosaur skull shows a three-dimensional effect.

WEB LINK

10.5 Review

Summary

- Polarized light is produced using filters to selectively block the transmission of light waves.
- Linearly polarized, or plane polarized, light is entirely polarized in one direction that is perpendicular to the direction of propagation.
- Selective absorption, reflection, and scattering are three ways that polarized light can be produced from unpolarized light.
- Malus's law states how the transmitted intensity of light through a polarizer is related to the incident intensity of light: $I_{out} = I_{in} \cos^2 \theta$.
- Polarization filters have many uses, including stress analysis in materials, sunglasses, and the design and production of LCD displays.
- Simple sugars, such as fructose and sucrose, are optically active molecules that rotate in the direction of the polarization of light.
- By applying different voltages to different areas of a liquid crystal, an LCD device can form various patterns of light and dark regions corresponding to letters or numbers.

Questions

1. Describe the characteristics of unpolarized light and partially polarized light. K/U C
2. You are shopping for sunglasses and want to test whether a pair you like has polarizing lenses or simply darkened plastic lenses. Describe two ways you could quickly test them. K/U A
3. Briefly describe how selective absorption, reflection, and scattering polarize light. K/U C
4. A polarizer and an analyzer have perpendicular axes, so that light through them is blocked. Describe what will happen, and why, when you place between them a Polaroid sheet with its transmission axis
   (a) parallel to the transmission axis of the polarizer
   (b) parallel to the transmission axis of the analyzer
   (c) at a 45° angle to the two other axes K/U T/I A
5. The sky often looks very different when viewed through polarizing sunglasses. Explain what causes this effect. K/U C
6. The light reflected from the surface of a still pond is observed through a polarizer. How can you tell whether the reflected light is polarized? K/U
7. Using what you know about polarization, explain why the sky appears blue. K/U
8. You are viewing a selective polarization experiment through protective goggles. The original intensity of the incident polarized light is 250 candelas, and the resultant light is 17 % as intense. Determine the polarization angle of the incident light with respect to the polarization angle of the filter. T/I
9. A flashlight is directed at the flat side of a piece of quartz with an index of refraction of 1.54. The light travels through air. Calculate the angle of incidence that results in perfectly polarized light. What is the name of this angle? K/U
10. Explain in your own words how materials are able to reflect polarized light when the light source is unpolarized. K/U C
11. On a sunny day, the reflection of the sky in a window can make it difficult to see through the window to the inside of the building. Describe how polarized sunglasses can make it easier to see through the window. K/U C A
12. Is it possible for light intensity to be unaffected by a polarization filter? Explain your answer. K/U C A
13. One method of creating three-dimensional images in movies relies on polarization technology to create the optical illusion of a three-dimensional image. Research 3D technology and its use of polarization. Summarize your findings in a format of your choice. C A
14. Theatres showing movies that appear three-dimensional frequently make polarizing eyeglasses available to their patrons. Research the role that polarizing eyeglasses have in producing the 3D appearances of the images, and explain your findings orally to a fellow student. T/I C A

WEB LINK