Polarized Light

6

If the end of a stretched rope is shaken up and down, as shown in Fig. 2.1, a train of transverse waves will travel down the rope. As the wave progresses, all segments of the rope will be set into vibration in a vertical plane. Similarly, moving the end of the rope side to side, or, for that matter, in any single direction, will produce transverse waves that are *plane polarized*.

Polarization is not restricted to mechanical waves, such as those we excite on a rope. In the late seventeenth century, Christiaan Huygens discovered that light may also be polarized. A physical explanation of the phenomenon was somewhat long in coming, however. A theory based on the transverse nature of light waves, proposed by Robert Hooke in 1757, was verified by Thomas Young in 1817. Longitudinal waves, such as sound, cannot be polarized.

In Sect. 2.11, we learned that light waves are electromagnetic waves. As was noted there, Scottish physicist James Clerk Maxwell theorized that light occupied just a small portion of a much broader electromagnetic spectrum. According to Maxwell, all electromagnetic waves consist of mutually perpendicular electric and magnetic fields, as shown in Fig. 2.20. Heinrich Hertz verified Maxwell's theory with a series of experiments, one of which demonstrated the polarization of electromagnetic waves.

In the light waves that are emitted by common sources, such as light bulbs, candle flames, and even the Sun, the electric and magnetic fields are randomly oriented in the plane perpendicular to the direction of propagation, as shown in Fig. 6.1. Such light is unpolarized. However, it can become polarized through a variety of processes involving the interaction of light with matter. These include selective absorption, reflection, birefringence, and scattering, which we will now discuss.

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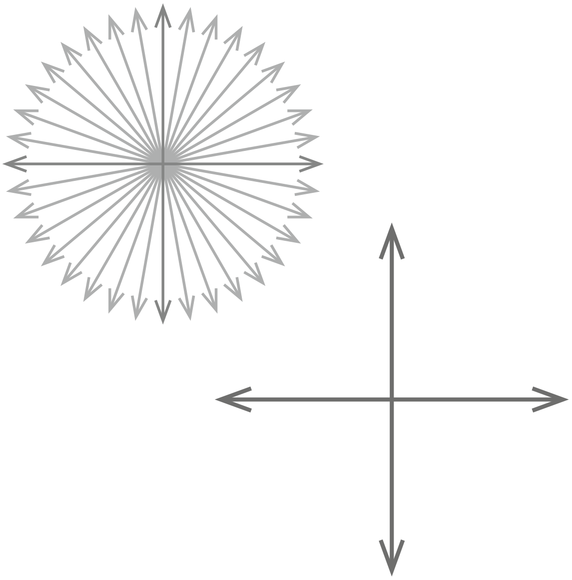


Fig. 6.1 Two representations of unpolarized light

6.1 Polarization by Selective Absorption

A *dichroic* material selectively absorbs light with **E**-field (electric field) vibrations in a certain direction but passes light with **E**-field vibrations perpendicular to this direction. The mineral tourmaline is an example of a natural dichroic material, but manufactured Polaroid H-sheets are also dichroic.

To understand selective absorption, consider a rope passing through two sets of slots or picket fences, as shown in Fig. 6.2. A vertically polarized wave on the rope easily passes through the vertical slots but is unable to traverse the horizontal slots. If the polarization plane of the rope is neither horizontal nor vertical, only the horizontal or vertical component of its vibration will be transmitted, as shown. Similarly, when unpolarized light passes through a dichroic material, only light with **E**-field vibrations in a certain direction is transmitted, so polarized light emerges.

An ideal polarizer should transmit exactly half of the unpolarized light that is incident on it and absorb the other half. We can understand this if we think of unpolarized light as having its **E**-field randomly distributed in all directions perpendicular to the direction of propagation. Each vibrating **E**-field can be thought of as being made up of a component along the axis of polarization of the dichroic crystal (like the direction of the slots in Fig. 6.2) and a component perpendicular to them. The components parallel to this axis add up to produce a polarized beam of light, while the components perpendicular to the axis are absorbed. The intensity of the polarized beam that emerges will be half as great as that of the unpolarized beam that entered the polarizer. In real materials, the intensity of the polarized beam will be a little less than 50% of the unpolarized beam because there is always some

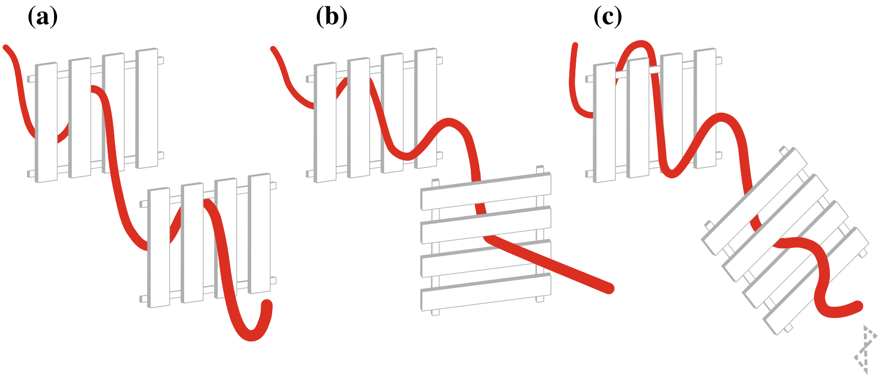


Fig. 6.2 Model of polarization. Vertical vibrations in a rope (**a**) can readily pass through a set of vertical slots, but are blocked by a horizontal set (**b**). Vibrations in an oblique plane (**c**) are partially transmitted, partially blocked

loss in the material (just as window glass transmits slightly less than 100% of the incident light).

We have arbitrarily selected the direction of the **E**-field (electric field) vibrations to designate the polarization direction of the light. We could have just selected as well the **B**-field (magnetic field) vibrations, but it would needlessly complicate things to keep track of both fields. In most physics books, the **E**-field vibration direction is designated as the polarization direction, and the plane of polarization is the plane that includes the **E**-field vibration and the direction of propagation.

The light transmitted by tourmaline has a blue–green color and is therefore unsatisfactory for many applications. In 1852, W. B. Herapath discovered a synthetic polarizing material that transmits all colors about equally. Unfortunately, this material, called *herapathite* (a sulfate of iodoquinine), is a brittle crystalline substance that disintegrates easily.

The search for a durable, high-quality polarizing material continued until 1928 when Edwin Land found that he could embed herapathite crystals in sheets of plastic. In 1938, Land developed a more efficient polarizer called Polaroid H-film, nowadays simply referred to as Polaroid. Polaroid consists of long chains of polyvinyl alcohol molecules aligned on a plastic substrate. When the material is heated and stretched, the molecular chains become conducting.

Electrons may move freely along, but not between, the hydrocarbon chains found in Polaroid. Light with components of the **E**-field vibrations parallel to these molecular chains sets up electric currents in the chains. These currents dissipate energy. Components of the **E**-field perpendicular to the chains produce no electron motion and consequently pass through the material. Thus, only light with its **E**-field vibration at right angles to the molecular chains emerges from the polarizing material, and the axis of polarization of Polaroid is perpendicular to the direction of the molecular chains. An ideal polarizing filter should absorb 50% of the incident light. Actual Polaroid material absorbs slightly more than this.

Fig. 6.3 Crossed and uncrossed Polaroid filters

In Fig. 6.2b, we note that a set of vertical slots followed by a horizontal set would allow no vibrations to pass. Similarly, two Polaroid filters with their polarizing axes "crossed" (i.e., at right angles) will pass no light, as shown in Fig. 6.3. When light passes through two consecutive Polaroid filters, we call the first one the *polarizer* and the second one the *analyzer*. We can control the intensity of transmitted light by rotating either the polarizer or the analyzer.

Law of Malus

The intensity of light transmitted by two consecutive Polaroid filters can be calculated from the law of Malus:

$$I = \frac{1}{2} I_0 \cos^2 \theta, \tag{6.1}$$

where I_0 is the intensity of the light incident on the polarizer and θ is the angle between the polarizing axes of the polarizer and analyzer. Maximum transmission occurs when $\theta = 0$ or 180°, that is, when the polarizing axes are parallel (since the cosine of 0 is 1 and the cosine of 180° is −1); $I = 0$ when the axes are crossed (the cosine of 90° or 270° is zero).

▲ Example

Unpolarized light passes through two Polaroids whose axes are oriented at 60°. What percentage of the light transmitted through the first Polaroid (polarizer) will also pass through the analyzer?

Solution Substituting the given data into Eq. (6.1),

$$I = 1/2\, I_0 \cos^2(60^\circ)$$
$$I = 1/2\, I_0(0.25)$$
$$I/I_0 = 0.125 = 12.5\%$$

Three Polaroid Filters

If a third Polaroid filter is inserted between two crossed Polaroid filters, we note the following interesting effects:

1. If the axis of the third filter lines up with either the polarizer or the analyzer, no change in the transmitted light is noted (other than a slight absorption due to the color of the film). (Just as inserting a third picket fence whose pickets are either vertical or horizontal would have no net effect on the rope in Fig. 6.2b.)
2. If the axis of the third filter is at 45° to those of the crossed polarizer and analyzer, light will now pass through. That is because the light passing through the 45-degree filter is now polarized at 45° (and according to the law of Malus, its intensity is reduced to one-fourth) of I_0. Its intensity is therefore reduced again by one-half as it passes through the analyzer. Thus, the emerging light has one-eighth the intensity of the light originally incident on the polarizer. Careful study of Fig. 6.2c will help to explain this effect.
3. If the third filter is rotated (while the polarizer and analyzer remain crossed) , the light intensity will alternate from maximum to minimum each 45° rather than each 90°, as we observed when one of the filters is rotated in the two-filter experiment.

Later, we will see that placing other materials between crossed Polaroid filters leads to some very surprising effects.

6.2 Polarization by Reflection

Light reflected from a nonmetallic surface, such as water, snow, or glass, is generally partially polarized, which means that there are more **E**-field vibrations in a certain direction than perpendicular to that direction. The degree of polarization depends upon the angle of incidence and the nature of the reflector, as we shall see. French physicist Etienne Malus (who also discovered the law that carries his name) serendipitously discovered this while observing reflected sunlight from windows in the Luxembourg Palace (Paris) through a calcite crystal, which acted as an analyzer.

When light is incident on a surface such as glass or water, it is partly reflected and partly refracted, as we learned in Chap. 3. The plane of incidence includes the incident, reflected, and refracted light rays. If the incident light is unpolarized, 50% of its **E**-field vibrations will lie in the plane of incidence and 50% will be perpendicular to this plane. On the surface, atoms are set into vibration by the **E**-field vibrations of the incident light; these vibrating atoms reradiate light, which forms the reflected and refracted rays.

Ordinarily, the reflected light will have slightly more **E**-field vibrations perpendicular to the plane of incidence than in the plane, and the refracted ray will have slightly more **E**-field in the plane of incidence, so both rays will be partially polarized. At a particular angle of incidence, however, such that the reflected and

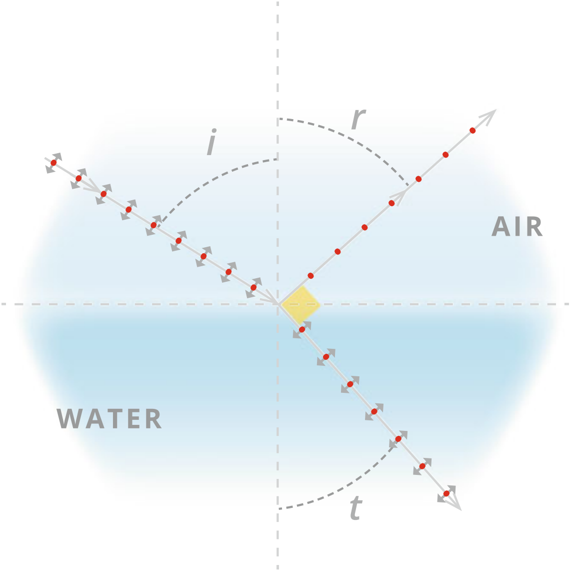


Fig. 6.4 When light is reflected at the Brewster (polarizing) angle, the reflected ray is completely polarized. The component of the **E**-field perpendicular to the page is represented by dots, the component parallel to the page by arrows

refracted light rays form a 90-degree angle with each other, the reflected light will be fully polarized with its **E**-field vibrations perpendicular to the plane of incidence, as shown in Fig. 6.4. This angle of incidence is called *Brewster's angle* in honor of David Brewster, who discovered the phenomenon in 1811.

Brewster's angle θ can be found from the relationship

$$\tan\theta = n_2/n_1, \tag{6.2}$$

where n_1 and n_2 are the indices of refraction of the media transmitting the incident and refracted rays, respectively ($n_1 = 1$ if the incident ray is in air).

▲ Example

Determine Brewster's angle for an air/diamond interface ($n_d = 2.42$).

Solution Substituting the given data into Eq. (6.2),

$$\begin{aligned}\tan\theta &= 2.42/1 = 2.42\\ \theta &= \tan^{-1}(2.42)\\ \theta &= 67.5^\circ.\end{aligned}$$

Applying this relationship to other materials, the Brewster angle is found to be 53° for an air/water interface and 56° for air/glass.

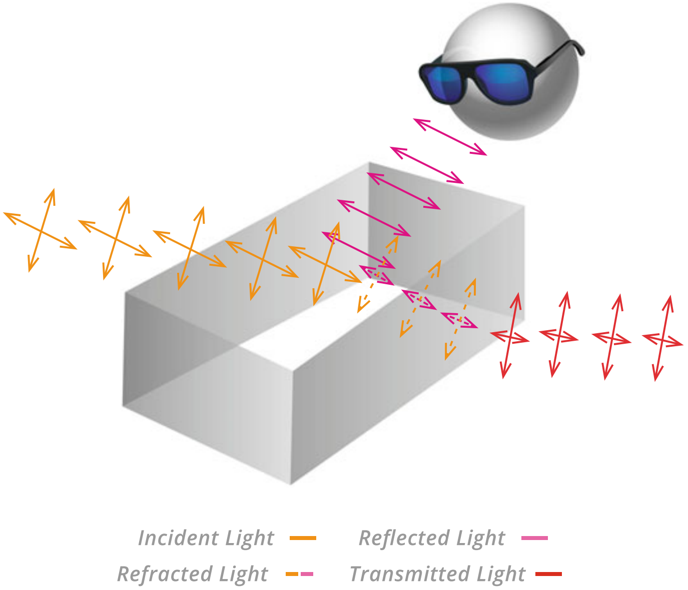


Fig. 6.5 Reduction of glare with Polaroid sunglasses. Reflected light from a surface is partially polarized in a horizontal plane and is thus attenuated by Polaroid glasses with vertical polarization axes

Note that the index of refraction can be determined by measuring Brewster's angle. This is particularly useful in the case of opaque materials where the transmitted light is strongly absorbed, making the usual Snell's law techniques (Sect. 4.3) quite useless. Polarization by reflection also makes it easy to determine the axis of a Polaroid filter or sheet of polarizing material that is not marked.

Understanding the polarization of light by reflection allows drivers, fishermen, and skiers to reduce the glare from road, water, and snow surfaces by wearing Polaroid sunglasses having their axes of polarization in the vertical direction. The reflected glare, which is at least partially polarized in the horizontal direction, is reduced by the Polaroid sunglasses (see Fig. 6.5).

Polaroid filters are very useful in photography. They can be used to reduce glare or increase the contrast between clouds and sky, for example.

6.3 Polarization by Double Refraction: Birefringence

In isotropic media, such as glass and water, the speed of light is the same in all directions, and each medium has a single index of refraction. Anisotropic crystals, such as calcite and quartz, on the other hand, have two indices of refraction. They are said to be *doubly refracting* or *birefringent*. The Danish scientist Bartholinus is credited with discovering the phenomenon of double refraction in 1670.

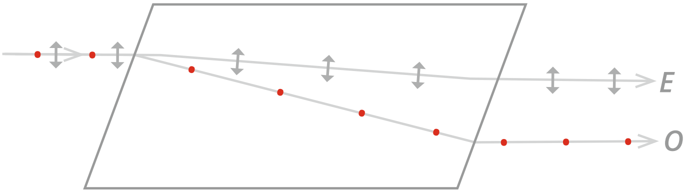
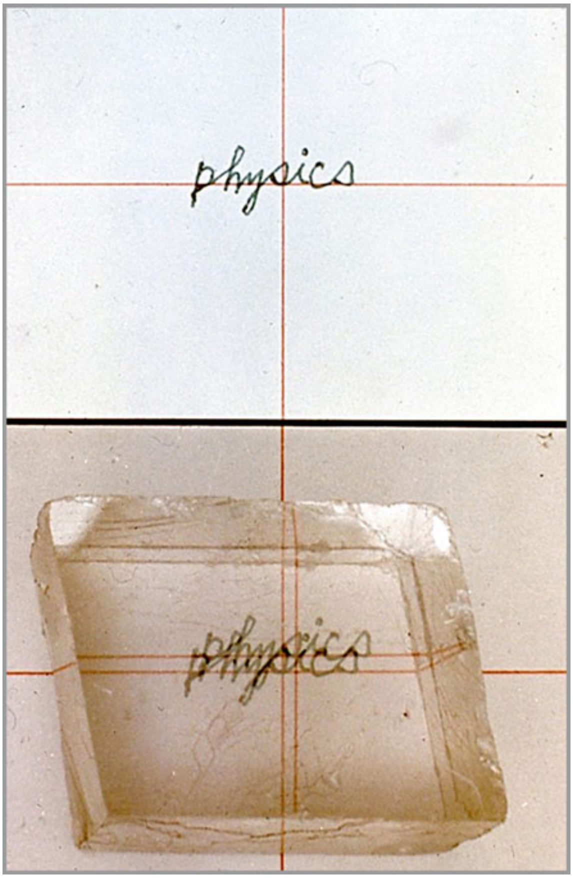


Fig. 6.6 Double refraction in a calcite crystal separates the unpolarized light into two plane-polarized components

When a ray of unpolarized light enters a birefringent crystal, it divides into two rays: an ordinary ray and an extraordinary ray. These rays have different speeds and are polarized at right angles to each other. The ordinary ray refracts according to Snell's law (Sect. 4.3), but the extraordinary ray follows a different path, as shown in Fig. 6.6. Only when light travels along a special path, the *optic axis* of the crystal, do the rays remain together.

Fig. 6.7 Double refraction in calcite (Courtesy of Kodansha, Ltd.)



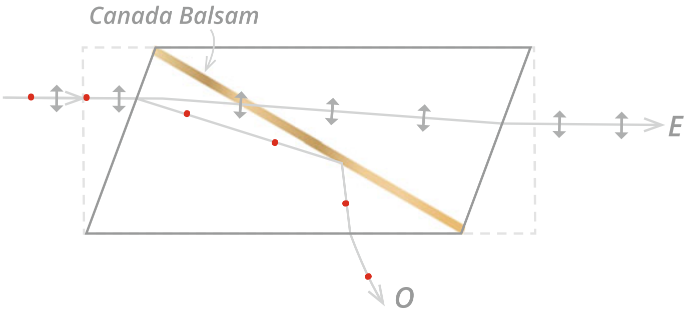


Fig. 6.8 Nicol prism

Two rays generally emerge from a birefringent crystal, giving rise to a double image, as shown in Fig. 6.7. Using a Polaroid analyzer, either ray can be extinguished while the other remains visible, verifying the unique polarization of each ray.

Prior to the invention of Polaroid sheets, calcite crystals were the principal means for obtaining polarized light in the laboratory. A *Nicol prism* is formed by joining two halves of a calcite crystal with Canada balsam adhesive, as shown in Fig. 6.8.

Light entering the prism is split into ordinary and extraordinary rays, as indicated in Fig. 6.8. The index of refraction of Canada balsam (n = 1.530) is between the two indices of calcite (1.658 for the ordinary ray and 1.486 for the extraordinary ray). The ordinary ray arrives at the interface with an angle greater than the critical angle (see Sect. 4.5) and is totally internally reflected; the extraordinary ray is transmitted. Both emerging rays are polarized. Polarizing prisms in optical instruments work on this same general principle.

6.4 Polarization by Scattering

Gas molecules in Earth's atmosphere scatter sunlight in all directions. This scattering is responsible for blue skies, red sunsets, and atmospheric polarization.

In 1871, Lord Rayleigh showed that the amount of light scattered depends on the size of the scattering molecules and the wavelength of light. In fact, the intensity of the scattered light is proportional to $1/\lambda^4$, where λ is the wavelength of the light. Shorter wavelengths, such as blue and violet, are scattered more effectively than longer wavelengths, such as red and orange; this is why the sky appears blue. At sunrise and sunset, the Sun's light travels near the surface of Earth, and therefore through a longer atmospheric path, and encounters more scatterers. This increases the amount of blue light that gets scattered from the initially white sunlight, leaving the familiar reddish light of sunrises and sunsets.

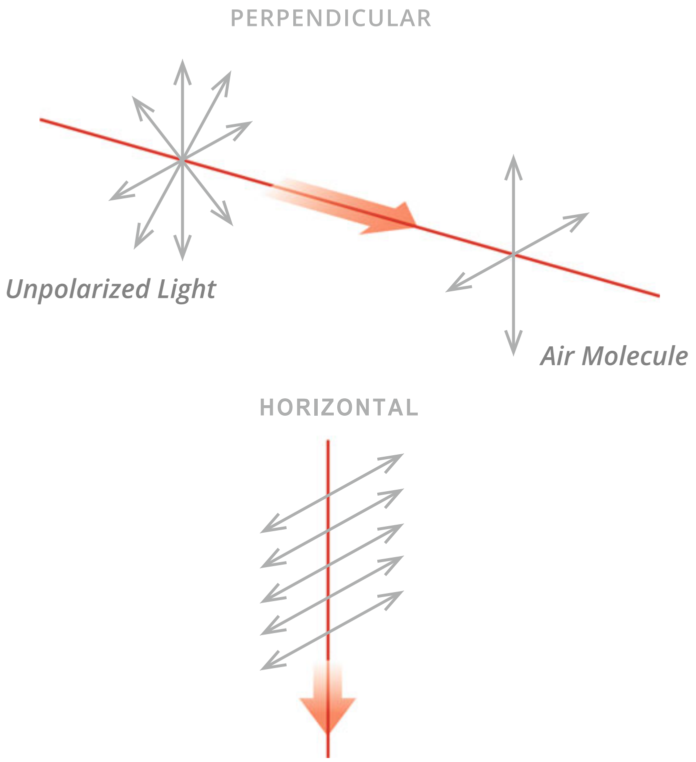


Fig. 6.9 Scattered sunlight will be polarized perpendicular to its direction of propagation. Downward scattered light will be polarized horizontally

Rayleigh scattering is also responsible for atmospheric polarization. When sunlight interacts with gas molecules, its **E**-field causes the molecules to vibrate and reradiate light that travels at right angles to the direction of propagation of the sunlight. Since the sunlight has no **E**-field in its direction of propagation, neither will the scattered light. The light that scatters to the side will be polarized vertically, while the light that scatters downward will be polarized horizontally, as shown in Fig. 6.9. An observer on the ground will see horizontally polarized light, as can be verified by viewing the sky through a Polaroid filter.

Some animals are capable of detecting polarized light. Nobel laureate Karl von Frisch demonstrated that bees use polarized light in navigation. Ants, fruit flies, and some fish also are known to be sensitive to polarized light.

In 1844, Wilhelm Karl von Haidinger suggested that at least some humans are sensitive to polarized light. A phenomenon called *Haidinger's brush* can be seen by some individuals as they stare at a blue sky in a direction perpendicular to the Sun. Observers sensitive to polarized light report a yellowish horizontal line superimposed on a field of blue.

Naturally occurring dichroic crystals called *macula lutea* are credited with a person's ability to detect polarized light. The yellow associated with Haidinger's brush results from the preferential absorption of blue light by the yellow pigment in the macula lutea.

6.5 Wave Plates

Wave plates or *retarders* are an interesting application of birefringence. Suppose that a calcite or other birefringent crystal is cut into a thin plate in such a way that the optic axis is parallel to the surface. If the **E**-field vibration of an incident light wave has components both parallel and perpendicular to the optic axis, then two separate waves will follow the same path through the plate but at different speeds. Thus they will get out of phase with each other (one of them is retarded compared to the other).

If the plate is the right thickness, it is possible for the slow wave to get 180° out of phase with the fast wave, which results in a rotation of the plane of polarization. Such a plate is called a *half-wave plate*, because 180° of phase shift is equivalent to a half-wavelength. Without going into detail, we will simply state that if the plane of polarization initially makes an angle θ with the fast axis, upon emerging it will have rotated through an angle 2θ.

A plate that is only thick enough for the slow wave to lag 90° behind the fast wave in phase is called a *quarter-wave plate.* Plane polarized light entering a quarter-wave plate emerges as elliptically polarized light and vice versa. Elliptically polarized light can be described by saying that the **E**-field vibration rotates as the light travels through space.

A special case of elliptically polarized light is circularly polarized light. Circularly polarized light is produced when plane polarized light is incident on a quarter-wave plate at an angle of 45° with respect to the fast and slow axes, as shown in Fig. 6.10. Composed of two waves of equal amplitude, differing in phase by 90°, the resulting **E**-field rotates in a circle around the direction of propagation, tracing a corkscrew path through space. If the **E**-field vibration of the light coming toward the observer is rotating counterclockwise, the light is said to be right-handed circular polarized. If the rotation is clockwise, the light is left-handed circularly polarized.

It is clear that if a half-wave plate or a quarter-wave plate is inserted between two crossed polarizers, cancellation of the light will no longer occur. Since a plate of a given thickness can act as a half-wave plate for only one wavelength (color) of light, inserting such a plate between crossed polarizers will produce light of that color. A plate whose thickness varies from place to place will show different colors. Many plastics are birefringent, and thus plastic objects act as retarders, displaying color when viewed between crossed polarizing filters.

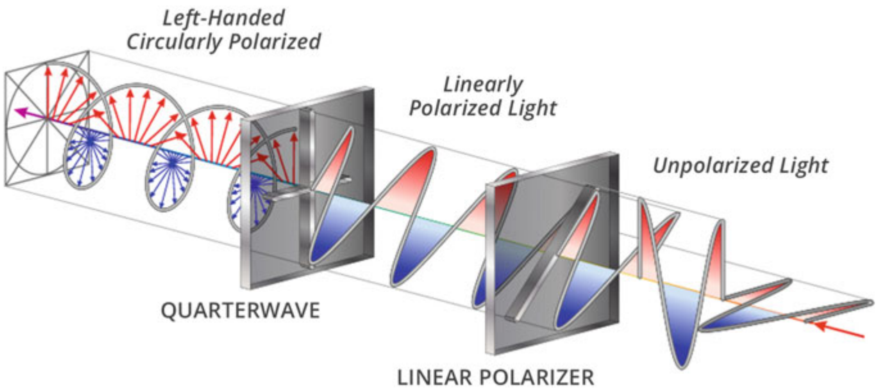


Fig. 6.10 Circularly polarized light is produced when plane polarized light, produced by a linear polarizer, is incident on a quarter-wave plate at an angle of 45° with respect to the fast and slow axes (Fouad A. Saad/Shutterstock.com)

Cellophane tape is also birefringent, so it is possible to create rather dramatic effects by applying multiple layers of cellophane tape to a glass plate so that the tape thickness varies, and then placing the plate between two crossed polarizers. Furthermore, the colors can be changed dramatically by rotating one of the polarizers. Several museums display large panels with vivid colors created in this manner (see Sect. 6.8).

A crumpled sheet of cellophane between two Polaroids will show a profusion of multicolored regions that vary in hue as one of the Polaroids is rotated. These *interference colors*, as they are generally called, arise from the wavelength dependence of the retardation. Interference colors can also be observed by placing such materials as mica insulators, ice, or a stretched plastic bag between the Polaroids.

6.6 Photoelasticity

In 1816 Sir David Brewster discovered that some materials become birefringent under stress. This phenomenon is called *photoelasticity* or *stress birefringence*. The effective optic axis is in the direction of the stress, and the induced birefringence is proportional to the stress. As shown in Fig. 6.11, you can observe photoelasticity by placing objects such as plastic forks, knives, and spoons between two crossed Polaroids.

Engineers make extensive use of photoelasticity to determine stress in bridges, buildings, and other structures. A scale model is constructed of some transparent photoelastic material such as plexiglass. This scale model is stressed as it is viewed between crossed Polaroids, so that lines of stress become apparent. Stress lines in molded glass for automobile windshields can likewise be made visible.

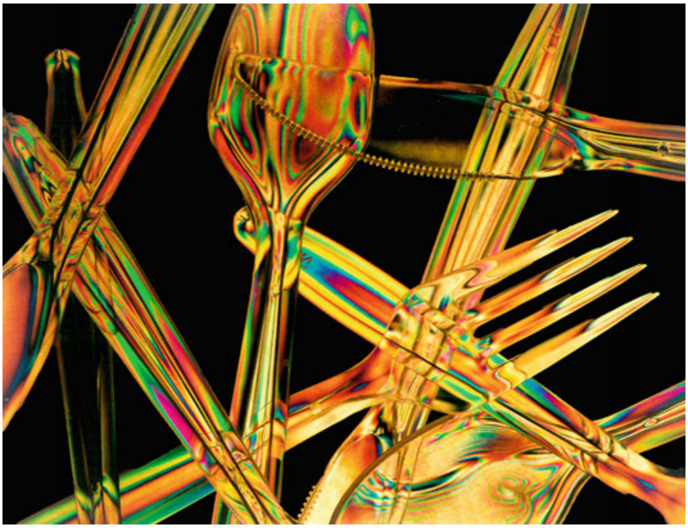


Fig. 6.11 Plastic spoons, knives, and forks exhibit stress birefringence when placed between crossed Polaroids (Carly Sobecki—American Association of Physics Teachers High School Photo Contest)

For many years, architects, art historians, and scientists debated whether the upper flying buttresses and pinnacles of Europe's Gothic cathedrals were decorative or functional. Princeton professor Robert Mark used photoelasticity to clarify the

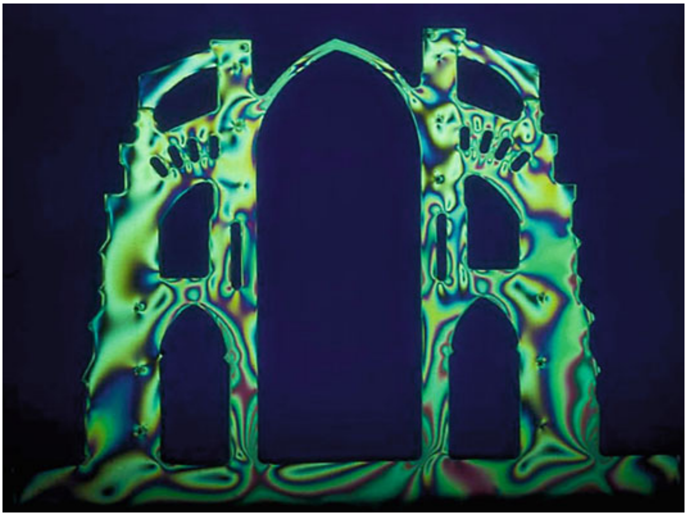


Fig. 6.12 Photoelastic model cross section of flying buttresses showing stress (Courtesy of Robert Mark)

problem by building models of sections of the Amiens, Chartres, and Bourges cathedrals from epoxy plastic. The plastic was heated under load to permit deformation, and cooled back to room temperature. When observed between crossed polarizers, the "frozen" stress patterns in the models provided the desired evidence: the flying buttresses and pinnacles were indeed crucial in guaranteeing the integrity of the Gothic structures in high winds, as shown in Fig. 6.12.

6.7 Optical Activity

Certain materials are capable of rotating the plane of polarization. Such materials, said to be *optically active*, include sugar solutions, corn syrup, turpentine, aniline, amino acids, and some crystals. The rotation per unit length of travel is generally measured by placing a sample between a polarizer and an analyzer in a polariscope.

Optical activity was first observed by Dominique Arago in 1811 when he observed that polarized light underwent a continuous rotation as it propagated along the optic axis in quartz. Another French physicist, Jean Baptiste Biot, observed the same effect in liquids such as turpentine, and he observed that some substances rotated the plane of polarization clockwise while others rotated it counterclockwise. Materials that rotate the plane of polarization clockwise are called *dextrorotatory* (or *d*-rotatory) while materials that rotate it counterclockwise are called *levorotatory* (or *l*-rotatory). (*Dextro* and *levo* are the Latin designations for right and left, respectively.) In 1822, Sir John Herschel recognized that *d*-rotatory and *l*-rotatory behavior in quartz resulted from two different crystallographic structures or arrangements of the SiO_2 molecules.

Optical activity can be described phenomenologically by thinking of linearly polarized light as being composed of two circularly polarized beams rotating in opposite directions. These two beams propagate at different speeds, and thus they recombine to give linearly polarized light with a different plane of polarization than it had when it entered. This simple description was first proposed by Fresnel in 1825.

Two or more compounds with the same molecular formula but different properties are called *isomers*. Molecules that are mirror images of each other are called *optical isomers*. (Your right hand could be considered an optical isomer of your left.) Optical isomers rotate polarized light in opposite directions.

When organic molecules are synthesized in the laboratory, an equal number of *d*- and *l*-isomers are generally produced with the result that the compound is optically inactive. However, this is not the case in natural organic substances. The natural sugar sucrose is always *d*-rotatory, as is the simple sugar dextrose or *d*-glucose, which is the most important carbohydrate in human metabolism. Evidently living things can somehow distinguish between optical isomers.

Fig. 6.13 A composite of two photographs, one with a polarizing filter (on the right) and the other without. Note how the filter accentuates the clouds and produces more saturated colors (PiccoloNamek (https://commons.wikimedia.org/wiki/File:CircularPolarizer.jpg), "CircularPolarizer", https://creativecommons.org/licenses/by-sa/3.0/legalcode)

6.8 Applications of Polarized Light in Art

▲ Photography

Photographers frequently make use of polarized light. Air molecules polarize light more effectively than do the larger water molecules and dust particles found in clouds. A photographer may take advantage of this differential polarization by placing a polarizing filter over the camera lens to accentuate clouds in a photograph, as seen in Fig. 6.13. Similarly, glare may be reduced through the use of polarizing filters.

▲ Tape Art

The birefringent nature of cellophane tape makes it possible to produce beautiful art from an otherwise colorless transparent material. In 1967, realizing the artistic potential of birefringence, artist Austine Wood Comarow invented Polage® Art, a name she derived from "polarize" and "collage."

Austine creates her stunning art by placing a drawing under a sheet of glass beneath which she positions polarizing material. She then cuts cellophane shapes that follow the lines of her drawing. To produce a desired color, she may use multiple layers, some at varying angles to each other. Since cellophane contains no pigments, the collage appears colorless to the unaided eye (see Fig. 6.14). This necessitates the wearing of polarizing sunglasses during the creation process. When ready for display, Austine places a second polarizing sheet, the analyzer, on top of the finished design, which, as almost by magic, reveals previously invisible shapes and colors.

Austine often animates her art with the use of a motorized analyzer. The effect of a rotating polarizer is seen in Fig. 6.15, which reveals three stages of the transformation of her appropriately titled *Hidden Treasure*.

Fig. 6.14 A collage consisting of pieces of cellophane appears colorless to the unaided eye (Courtesy of Austine Wood Comarow)

Fig. 6.15 A rotating analyzer produces a continuous flow of imagery in Austine Wood Comarow's Polage *Hidden Treasure*. Comarow's creations are on display in museums, science centers, offices, and homes all over the world (Courtesy of Austine Wood Comarow)

Austine's work has been displayed in numerous museum installations and is found in corporate collections worldwide. A sample of her extensive portfolio may be viewed at https://www.austine.com/polage-art-grid. After seeing her amazing creations, you may wish to try your hand at producing your own tape art. To learn how, see "Transparent tape art" in "Home and Classroom Demonstration."

▲ 3D Movies

The use of polarization in the production of three-dimensional (3D) effects in movies has evolved over the years. Early on, two cameras were used to record the action from slightly different perspectives. When the movie was shown, two projectors, each equipped with polarizing filters, were used. As is shown in Fig. 6.16,

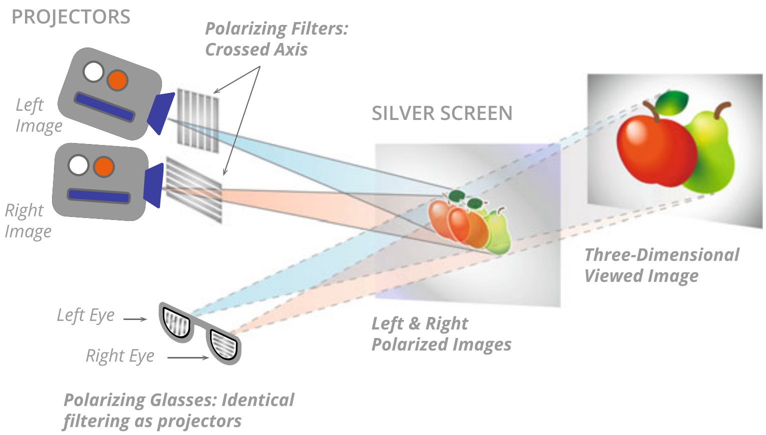


Fig. 6.16 At one time, three-dimensional (3D) movies employed linearly polarized light to produce a sense of depth

the filters' axes of polarization were at right angles to each other. A metallic screen was used so as not to alter the polarization of the projected images (as the glass beads of an ordinary projection screen would do).

The movie was viewed through polarizing filters whose axes of polarization were aligned to match those of the filters on the projectors. This insured that only one image was seen by each eye. A sense of depth was created in the brain as it combined these distinct images.

A disadvantage of using linear polarization is the requirement that the viewer's head remain level. Tilting the head sideways results in "ghost images," a bleeding together of left and right channel images. Furthermore, the alignment and synchronization of two projectors must be addressed.

Using circularly polarized light, modern technology offers a solution to both of these problems. Instead of using two projectors, the current system uses a single digital video projector that alternately projects right-eye and left-eye frames 144 times per second. Acting as a quarter-wave plate, a liquid crystal modulating device located in front of the projector circularly polarizes each frame in step with the projector. Frames intended for the right eye are circularly polarized in a clockwise direction, and vice versa.

Viewing is done with glasses whose lenses consist of a quarter-wave plate and a linear polarizer. The lenses are oppositely polarized so that each eye sees a different image. As with a projection and viewing system based on linear polarization, a metallic screen is used to maintain light polarization.

6.9 Summary

Transverse waves that vibrate in a single plane are said to be plane polarized. Light is polarized if the electric field (**E**-field) vibrations lie in a single plane. Light may be polarized by selective absorption, reflection, birefringence, and scattering.

Dichroic materials transmit light whose **E**-field vibrations are in one plane, but they absorb light whose **E**-field vibrations are perpendicular to this plane. Light reflected from smooth nonmetallic surfaces will be partially polarized, but at Brewster's angle it is completely polarized. Reflected glare from water and snow is greatly reduced when viewed through Polaroid sunglasses whose axes of transmission are oriented vertically. Doubly refracting or birefringent crystals, such as calcite and quartz, split an incident light ray into an ordinary and an extraordinary ray. These rays have different speeds and are polarized at right angles to each other. Light becomes polarized when it is scattered by molecules in our atmosphere, which can be observed by viewing the sky through a Polaroid filter.

Half-wave plates of birefringent material rotate the plane of polarization by delaying light with one plane of polarization more than the other. Quarter-wave plates convert plane polarized light to elliptically polarized light or vice versa. Inserting a half-wave plate between two crossed Polaroids produces interference colors.

Photoelastic materials become birefringent under applied stress. Scale models of structures, constructed from photoelastic materials, can be used to make stress lines visible. Optically active materials rotate the plane of polarization, either clockwise (dextrarotatary) or counterclockwise (levorotatory) as light passes through. Naturally occurring organic molecules, such as sugars, are generally dextrorotatory.

Applications of polarized light to art include photographic filters, 3D movies, and birefringent art.

◆ **Review Questions**

1. What is the difference between polarized light and unpolarized light?
2. Can sound waves be polarized? Explain your answer.
3. Describe four processes that may be used to polarize light.
4. Explain how a Polaroid filter works.
5. What is Brewster's angle?
6. How large is Brewster's angle for an air/water interface?
7. How does the transmitted light intensity compare to the incident light intensity when two ideal Polaroid filters have their axes (a) parallel and (b) perpendicular to each other?
8. When the Sun is in the east, would you expect to find the sky overhead polarized in the east–west direction or the north–south direction? Why?
9. Describe an experimental procedure that could be used to find the index of refraction of a nonmetallic material using a light source and a Polaroid filter.
10. Explain how a Polaroid filter placed over a camera lens increases the contrast between the clouds and sky.

11. What is photoelasticity? How is it used to study stress in structures?
12. Will Polaroid sunglasses reduce glare when worn upside down?
13. What is elliptically polarized light?
14. What are the disadvantages of using linearly polarized light in the production and projection of 3D movies?

▼ Questions for Thought and Discussion

1. When Polaroid sunglasses were first made commercially available, a small card with a transparent window in the center was attached. Prospective customers were told to rotate the card in front of either lens while wearing the glasses to ensure that they were buying Polaroid lenses, not just tinted glass. What do you suppose was observed? How did this procedure insure authenticity?
2. Explain how bees make use of polarization to navigate.
3. A piece of Polaroid material is inserted between two crossed polarizers so that its axis makes a 45° angle with theirs. What will be seen? Explain your answer.
4. Explain how a food chemist uses polarized light to determine the concentration of a sugar solution.
5. Describe how the direction of polarization of an unmarked Polaroid filter can be determined experimentally.

■ Exercises

1. Determine Brewster's angle for glycerin ($n = 1.47$).
2. Light reflected from the surface of a certain material is found to be completely polarized when the angle of incidence is 59°. What is the index of refraction of this material?
3. Unpolarized light passes through two Polaroids whose axes are oriented at 30°. What percentage of the light transmitted through the first Polaroid (polarizer) will also pass through the analyzer?
4. Determine the angle between transmission axes of two Polaroid filters that will produce an I/I_0 ratio equal to 0.25.

● Experiments for Home, Laboratory, and Classroom Demonstration

Home and Classroom Demonstration

1. **Polarization by reflection**. View light reflected from a highly polished floor, tabletop, blackboard, or puddle of water (sometimes referred to as *glare*) through a polarizing filter. Rotate the filter until the maximum amount of light is transmitted. Now rotate the filter through 90°. What happens to the intensity of the light as you rotate the filter? Why does this occur? Vary the angle of incidence by looking at light reflected at various distances away from you. At what angle of incidence does the greatest effect occur?

Use the filter to look at reflections from a variety of objects in your environment. What happens when you use the filter to view light reflected from a metallic surface such as a mirror? Does rotating the filter have any effect on the light intensity? What does this say about the light reflected from metallic surfaces? What happens when you try to use your filter to reduce the glare from the painted body of an automobile? Is this consistent with what you have learned about reflections from metals?

2. **Birefringence**. Birefringent materials such as calcite and quartz separate light into two components that possess mutually perpendicular polarizations. When stressed, plastic and glass may become birefringent. Viewed between Polaroid filters, the birefringence reveals itself as colored contours. Place a plastic object such as a tape cassette box, cellophane tape dispenser, protractor, or clear plastic fork between two Polaroid filters to make the stress lines visible. Colored patterns, revealing stresses introduced during the molding process, should be clearly visible. The stress lines in a clear plastic fork can be altered by squeezing the tines of the fork together.
3. **Polarized rainbow light**. Examine a rainbow with a Polaroid filter. For one orientation of the filter, the rainbow will be quite bright; rotating the filter will substantially reduce its intensity. This polarization is due to the reflection of light at the back of each raindrop.
4. **Polarization and liquid crystal displays**. Liquid crystal displays (LCDs) are commonplace. They are used in calculators, watches, instrument panels, and laptop computer screens. Do these devices produce their own light? To find out, observe a functioning display in a dark room. Based on your observation, what do you believe is an LCD's source of light? Now view an LCD through a Polaroid filter. What do you observe as you slowly rotate the filter? What does this tell you about the light from the display? In broad terms, how do you think an LCD works?
5. **Laptop computer display as a source of polarized light**. Dim the LCD display on a laptop computer until the screen becomes uniformly illuminated. At this point, graphics should no longer be visible. Slowly rotate a Polaroid filter between your eye and the screen. What do you observe? Now place a sample of birefringent material, such as clear plastic, quartz, or mica, between the screen and the filter. What do you see? Rotate the filter and observe the appearance of the sample. Wearing a pair of Polaroid glasses will facilitate the handling of samples.
6. **Transparent tape art**. By using pieces of transparent tape, such as clear packing tape or cellophane tape, and a pair of polarizing filters, you can create beautiful colored designs similar to Austine Wood Comarow's Polage. An acetate sheet, petri dish, or a glass plate can serve as your "canvas." Like any artistic creation, the designs you produce are limited only by your imagination. Detailed instructions for creating tape art may be found in Activity 8, Experiment 6.1.

7. **Viewing skylight**. View a portion of a clear blue sky through a polarizing filter, and note what happens as you rotate it. **Do not look directly at the Sun!** Look at other portions of the sky and note the change in brightness you can accomplish in different directions. In which direction is the sky most strongly polarized?
8. **Wax paper**. Slide a sheet of wax paper between two crossed polarizers and record what you observe. Check for evidence that the direction of polarization has changed.
9. **Corn syrup**. Put some colorless corn syrup in a beaker and place the beaker between crossed polarizers with a light source in line with them. Rotate one polarizer and carefully note what happens. If possible, try it with different depths of corn syrup.
10. **Photography with Polaroid filters**. Photograph scenes with and without a Polaroid filter in front of the camera lens and compare them. Some suggested scenes: glare of sunlight on water and pavement; reflection of an overhead light from a polished floor (at different angles of incidence) ; clouds against a blue sky, looking north, south, east, and west.
11. **Edible birefringents**. Home and Classroom Demonstration Experiment 8 in Chap. 4 showed how to make edible lenses, prisms, and light pipes from unflavored gelatin. If you examine gelatin between two polarizers, you will notice that it is birefringent—not surprising, given the long chain molecular structure of gelatin. Furthermore, it is photoelastic. Try bending and squeezing a gelatin strip to see color patterns resulting from stress-induced birefringence.

Laboratory (See Appendix J)

6.1 Exploring Polarized Light

Glossary of Terms

analyzer A polarizer used to analyze polarized light or the second of two polarizers used to control the intensity of transmitted light.

birefringence Splitting of light into two rays by anisotropic materials having two indices of refraction. Double refraction.

circularly polarized light Light composed of two waves of equal amplitude, differing in phase by 90°.

Brewster's angle Angle of incidence (or reflection) for which the reflected light is totally polarized.

dichroic Materials that absorb light whose **E**-field vibrations are in a certain direction.

elliptically polarized light Light with an **E**-field vibration that rotates as the light travels through space.

half-wave plate Birefringent material of the right thickness to retard one ray 180° with respect to the other so that the plane of polarization is rotated.

Malus's law Intensity of polarized light transmitted through an analyzer is the incident intensity times $\cos^2 \theta$, where θ is the angle between the axes of the polarizer and analyzer.

Nicol prism A calcite prism used to produce or analyze polarized light. Two halves of a calcite crystal are cemented together with Canada balsam.

optical activity Rotation of the plane of polarization of transmitted light (clockwise in some materials, counterclockwise in others).

photoelasticity Some materials become birefringent under stress.

plane polarized waves Transverse waves (such as light) with vibrations oriented in one plane.

polarizer Used to polarize light, or the first of two polarizing filters used to control light intensity.

Polaroid Synthetic polarizing material developed by Edwin Land that consists of long chains of molecules that absorb light polarized in a certain plane.

quarter-wave plate Birefringent material of the right thickness to retard the phase of one ray by 90° with respect to the other so that plane polarized light is changed to elliptical and vice versa.

Rayleigh scattering Atmospheric scattering of sunlight, which depends on the size of the scattering molecules and the wavelength of the light.

wave plate or retarder A thin plate of a birefringent material with the optic axis parallel to the surface so that it transmits waves having their **E**-fields parallel and perpendicular to the optic axis at different speeds.

Further Reading

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Jewett, J. W. (1994). *Physics Begins with an M ... Mysteries, Magic and Myth.* Boston: Allyn and Bacon.