Optics
Polarization
Birefringence

Lana Sheridan

De Anza College

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Last time

- the interferometer and gravitational waves
- polarization
- Brewster angle
Overview

- polarization
- birefringence
- Rayleigh scattering
We can obtain an expression relating the polarizing angle to the index of refraction of the reflecting substance by using Figure 38.28.b. From this figure, we see that $\theta_1 > 90^\circ > \theta_2$, therefore, $\theta_2 = 90^\circ - \theta_1$. Using Snell's law of refraction (Eq. 35.8) gives

$$n_2 \sin \theta_1 = n_1 \sin \theta_2$$

Because $\sin \theta_2 = \sin (90^\circ - \theta_1) = \cos \theta_1$, we can write this expression as

$$n_2 / n_1 = \sin \theta_1 / \cos \theta_1$$

which means that

$$\tan \theta_1 = n_2 / n_1$$

This expression is called Brewster's law, and the polarizing angle $\theta_p$ is sometimes called Brewster's angle, after its discoverer, David Brewster (1781–1868). Because $n$ varies with wavelength for a given substance, Brewster's angle is also a function of wavelength.

We can understand polarization by reflection by imagining that the electric field in the incident light sets electrons at the surface of the material in Figure 38.28.b into oscillation. The component directions of oscillation are (1) parallel to the arrows shown on the refracted beam of light and therefore parallel to the reflected beam and (2) perpendicular to the page. The oscillating electrons act as dipole antennae radiating light with a polarization parallel to the direction of oscillation. Consult Figure 34.12, which shows the pattern of radiation from a dipole antenna. Notice that there is no radiation at an angle of $\theta = 0$, that is, along the oscillation direction of the antenna. Therefore, for the oscillations in direction 1, there is no radiation in the direction along the reflected ray. For oscillations in direction 2, the electrons radiate light with a polarization perpendicular to the page. Therefore, the light reflected from the surface at this angle is completely polarized parallel to the surface.

Polarization by reflection is a common phenomenon. Sunlight reflected from water, glass, and snow is partially polarized. If the surface is horizontal, the electric field vector of the reflected light has a strong horizontal component. Sunglasses made of polarizing material reduce the glare of reflected light. The transmission axes of such lenses are oriented vertically so that they absorb the strong horizontal component of the reflected light. If you rotate sunglasses through 90°, they are not as effective at blocking the glare from shiny horizontal surfaces.

The dipoles in the surface cannot create a ray that has an E-field oscillating in the direction that the ray travels.

When the reflected and refracted rays are perpendicular, the reflected ray is completely polarized parallel to the surface.
Creating Polarized Light: by Reflection

The value of the incident angle for the reflected and transmitted rays to be perpendicular, \( \theta_p \) is called **Brewster’s angle**.

Notice, \( \theta_2 = 90^\circ - \theta_p \). From Snell’s Law:

\[
\begin{align*}
    n_1 \sin \theta_p &= n_2 \sin(90^\circ - \theta_p) \\
    n_1 \sin \theta_p &= n_2 \cos(\theta_p)
\end{align*}
\]

So,

\[
\theta_p = \tan^{-1} \left( \frac{n_2}{n_1} \right)
\]
Creating Polarized Light: Birefringent Materials

Calcite and quartz are examples of crystals that have a special property: the speed of light (phase velocity) is not the same in all directions. The speed of a ray depends on both the direction it travels and the direction of polarization.

\[ S \] is a point source emitting in all directions: the wavefronts don’t remain spherical for one type of polarization (E-ray).
Creating Polarized Light: Birefringent Materials

There are two refracted rays in a birefringent material:

- **O ray** and **E ray**

These two rays are polarized in mutually perpendicular directions.

The ordinary ray (O) and the extraordinary ray (E). Both have different polarizations.
Engineers often use this technique, called optical stress analysis, in designing structures ranging from bridges to small tools. They build a plastic model and analyze it under different load conditions to determine regions of potential weakness and failure under stress. An example of a plastic model under stress is shown in Figure 38.32.

Polarization by Scattering

When light is incident on any material, the electrons in the material can absorb and reradiate part of the light. Such absorption and reradiation of light by electrons in the gas molecules that make up air is what causes sunlight reaching an observer on the Earth to be partially polarized. You can observe this effect—called scattering—by looking directly up at the sky through a pair of sunglasses whose lenses are made of polarizing material. Less light passes through at certain orientations of the lenses than at others.

Figure 38.33 illustrates how sunlight becomes polarized when it is scattered. The phenomenon is similar to that creating completely polarized light upon reflection from a surface at Brewster's angle. An unpolarized beam of sunlight traveling in the horizontal direction (parallel to the ground) strikes a molecule of one of the gases that make up air, setting the electrons of the molecule into vibration. These vibrating charges act like the vibrating charges in an antenna. The horizontal component of the electric field vector in the incident wave results in a horizontal component of the vibration of the charges, and the vertical component of the vector results in a vertical component of vibration. If the observer in Figure 38.33 is looking straight up (perpendicular to the original direction of propagation of the light), the vertical oscillations of the charges send no radiation toward the observer. Therefore, the observer sees light that is completely polarized in the horizontal direction as indicated by the orange arrows. If the observer looks in other directions, the light is partially polarized in the horizontal direction.

Variations in the color of scattered light in the atmosphere can be understood as follows. When light of various wavelengths \( l \) is incident on gas molecules of diameter \( d \), where \( d, l \), the relative intensity of the scattered light varies as \( 1/l^4 \). The condition \( d, l \) is satisfied for scattering from oxygen (\( \text{O}_2 \)) and nitrogen (\( \text{N}_2 \)) molecules in the atmosphere, whose diameters are about 0.2 nm. Hence, short wavelengths (violet light) are scattered more efficiently than long wavelengths (red light). Therefore, when sunlight is scattered by gas molecules in the air, the short-wavelength radiation (violet) is scattered more intensely than the long-wavelength radiation (red). When you look up into the sky in a direction that is not toward the Sun, you see the scattered light, which is predominantly violet. Your eyes, however, are not very sensitive to violet light. Light of the next color in the spectrum, blue, is scattered with less intensity than violet, but your eyes are far more sensitive to blue light than to violet light. Hence, you see a blue sky. If you look toward the west at sunset (or toward the east at sunrise), you are looking in a direction toward the Sun and are seeing light that has passed through a large distance of air. Most of the blue light has been scattered by the air between you and the Sun. The light that survives this
Scattering depends on Wavelength

When light is scattered by particles much smaller than the wavelength of the radiation (Rayleigh scattering), the intensity of the scattered light goes as:

\[ I = I_0 \frac{\text{(const.)}}{\lambda^4} (1 + \cos^2 \theta) \]

\((\theta \text{ is the scattering angle.})\)

Shorter wavelengths (violet) are scattered more intensely.

Rayleigh scattering gives the atmosphere its blue color
Why the Sky is Blue: Rayleigh Scattering

The amount (intensity) of the light scattered by small particles depends on the wavelength:

\[ I \propto \frac{1}{\lambda^4} \]

shorter wavelength light is scattered more

Rayleigh scattering gives the atmosphere its blue color

\[ \text{Percent Scattering of Direct Sunlight} \]

Wavelength (nm)

0 450 500 550 600 650
0 5 10 15 20 25

shorter wavelength light is scattered more

opalescent glass

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1Left, Robert A. Rohde, Wikipedia; right, user optick, https://www.flickr.com/photos/optick/112909824/
Questions we wanted to answer:

- How does an airplane wing create an upward lifting force?
- Why does hot metal start to glow red when heated?
- When a block of ice is left out at room temperature and pressure it will melt. Why does this happen?
- Why is it not uncommon to see a glass cup fall and shatter, but we never see a pile of broken glass reassemble itself into a cup?
- Why can you hear someone’s voice when they are still around a corner from you, but you can’t see them?
- Why is the sky bright during the day? Why is the daytime sky blue?
Summary

- polarization
- birefringence
- scattering

Final Exam 9:15-11:15am, Tuesday, June 26.

Homework Serway & Jewett:

- prev: Ch 38, onward from page 1182. OQs: 1, 7; Probs: 45, 49, 51, 63, 65, 70
- new: Ch 38, onward from page 1182. Prob: 75