4. Polarization and Polarizers

Polarized Light

Earlier, we discussed polarization as the direction of a wave's displacement with respect to its motion. We mentioned that an electromagnetic wave is transversely polarized, which is fairly unambiguous because both the electric and magnetic fields oscillate perpendicular to the direction the wave travels. From here on, "polarization" may also mean the orientation of the plane of polarization. Recall that the plane of polarization of the wave is the plane containing the direction of motion and the direction of electric field oscillation. Light that is "polarized" in this sense is composed of electromagnetic waves that all oscillate in the same direction. For example, vertically polarized light would have its electric field oscillating up-and-down.

On one level we can just take this as a definition, but it is useful to note why we chose to define the polarization this way instead of using the magnetic field. For a wave oscillating in free space it does not make much of a difference if we defined the plane of polarization as the plane of oscillation of the electric field or the magnetic field. In fact, for an electromagnetic wave traveling in a vacuum it does not matter much what the polarization is at all. When this wave interacts with matter (when it's absorbed, scattered, reflected or refracted) then the polarization becomes important.

So why choose the electric field over the magnetic field for defining the polarization? When a light ray hits an object at rest, to a good approximation the charges are more or less at rest themselves so the magnetic field from the wave cannot exert a force on the charges. The electric field, however, can exert a force on the charges and get them to move. The magnetic field doesn't play an important part in this because even if the particles are moving significantly we know that they must be traveling slower than the speed of light \(c\). The magnitude of the electric field \((E_0 = c B_0)\) for an electromagnetic wave, so we see that the magnitude of the electric force on the charges is larger than that of the magnetic force on the charges!
Furthermore, we can easily figure out the direction of the electric force on particles. The force on the charge is in the direction of the field for a positive charge, or against the field for a negative charge. Compare this to the fifty-nine (or so) rules that we needed to learn for magnetic force! We choose to talk about the polarization in terms of the electric field because the electric force is much more convenient to discuss.

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**Polarizers**

The polarization of a wave depends on how the wave was produced and what it interacted with. Lasers typically (but not always) produce polarized beams. Light from thermal sources (such as an incandescent light bulb or the sun) are produced by the random vibrations of atoms, so light is polarized completely differently at different times. We call these sources **unpolarized**. Some polarizations are preferentially reflected or absorbed by matter, so it's possible to polarize light by shining it onto a special kind of matter called a **polarizer**.

There are many materials which polarize light. Synthetic plastics (called polaroids) and natural crystals are common examples. The common feature among these materials is that they all have long linear chains of atoms which are oriented in one direction. Electrons in these media can travel more easily along the direction of the atomic chains. This allows the electric fields which are oriented in the direction of the atomic chains to transfer their energy to the electrons in the medium. The component of the electric field which is perpendicular to the atomic chains cannot give energy to the electrons, because the electrons cannot move in that direction. This means the wave component aligned with the atomic chains is absorbed, while the wave component nonaligned is transmitted.

If we are given any polarization of light we can break it into components: a component for which the polarization of the wave is in the parallel to the chains of molecules (which will be absorbed by the electrons) and a component which is perpendicular to the chains of molecules (which will pass through as it cannot be absorbed). We call the parallel axis the **absorption axis**, because this component of the light is absorbed. We call this perpendicular direction the **transmission axis** or **polarizer axis**, because light that passes through the polarizer is polarized in this direction.
The image above is a diagram of a polarizer. Because the electrons cannot oscillate in the direction of the polarizer axis, any light that passes through this polarizer will come out polarized in that direction (horizontally, in this diagram).

In general we may be interested in how much light gets through a given polarizer if the incident light has a given intensity \(I_0\). If the electric field is \(E_0\) and the angle between the polarization plane of the light and the polarization axis is \(\theta\) then we can break the field into two parts:

\[
\begin{align*}
E_{\text{absorbed}} &= E_0 \sin \theta \\
E_{\text{trans}} &= E_0 \cos \theta
\end{align*}
\]

The example below shows how these quantities affect transmitted intensity.

Example #1

Light polarized along a vertical axis, traveling into the page, hits a polarizer. The polarizing axis is 30° from the vertical. What is the intensity of the light coming out of the polarizer as a fraction of the intensity of incoming light? Which way is the light polarized?

Solution

We will call the amplitude of the electric field of the original wave \(E_0\), and we know that the initial electric field oscillates vertically. The polarization axis and the electric field are shown on the picture above. First we break the electric field into a part that is along the polarizer axis (which will be transmitted) and a part that is along the atomic chains of the material (which will be absorbed).
The magnitude of the electric field that makes it through the polarizer has a magnitude \(E_{\text{trans}} = E_0 \cos 30°\).

The intensity of the light that makes it through the polarizer is

\[
I = \frac{1}{2 \mu_0 c} (E_{\text{trans}})^2 = \frac{1}{2 \mu_0 c} E_0^2 \cos^2 30° = \left( \frac{1}{2 \mu_0 c} E_0^2 \right) \frac{3}{4}
\]

\(E_0\) is the initial magnitude of the field, so \(E_0^2/(2 \mu_0 c)\) is the initial intensity \(I_0\). Therefore we have

\[
I = \frac{3}{4} I_0
\]

So the outgoing light is polarized 30° from the vertical and has 3/4 the initial intensity.

As you just saw, the intensity of the light coming out is proportional to the transmitted electric field squared. We then have

\[
I_{\text{out}} = I_0 \cos^2 \theta
\]

This equation is sometimes referred to as Malus’s law. If unpolarized light travels through a polarizer, \(I_{\text{out}}\) is always half the initial intensity.

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