Physics 228

Today:
Polarization of Light
Polarizers
Reflection and Polarization
Birefringence
Polarization of Waves on a String

With a rope, you can make a wave traveling to the right with the displacement in the vertical or in the horizontal direction.

(a) Transverse wave linearly polarized in the \( y \)-direction

\[
\begin{align*}
\text{y} & \quad \text{x} \\
\text{z}
\end{align*}
\]

By swinging the end of rope around in a circle we generate a circularly polarized wave, which can be linearly polarized by a vertical slit.

The slit acts as a “linear polarizer”.

(b) Transverse wave linearly polarized in the \( z \)-direction

\[
\begin{align*}
\text{y} & \quad \text{x} \\
\text{z}
\end{align*}
\]

(c) The slot functions as a polarizing filter, passing only components polarized in the \( y \)-direction.
Polarizing Visible Light

- Polaroid filter absorbs light of one linear polarization, transmits the other.

- This polarizer is based on long, thin molecules that are aligned in the material.

- Polarizers based on other principles also exist, i.e., total internal reflection or polarizing properties of crystals.
An ideal polarizer transmits 50% of incident unpolarized light.
Polarizer and Analyzer

Crossed polarizers block all light!

**Malus’s Law:**

\[ I = I_M \cos^2 \theta \]
Crossed Polarizers

Two Polarizer Demo
I have 3 polarizers in a row, with the 1\textsuperscript{st} in the x direction, the 2\textsuperscript{nd} rotated 45\degree, and the 3\textsuperscript{rd} in the y direction. What fraction of the light that makes it through the 1\textsuperscript{st} polarizer also makes it through the 3\textsuperscript{rd} polarizer?

a) $0 = \cos(\phi_1 - \phi_3) = \cos(90)$. 

b) $1/4 = \cos^2(45) \times \cos^2(45)$. 

c) $1/2 = \cos(45) \times \cos(45)$. 

d) It depends on whether the light is in the $+x$ or $-x$ direction initially. 

e) It depends on whether the light is linearly polarized or circularly polarized.
Clicker Question

Three polarizing filters are stacked with the polarizing axes of the second and third filters oriented at 45° and 90°, respectively, relative to the polarizing axis of the first filter. Unpolarized light of intensity $I_0$ is incident on the first filter. The intensity of light emerging from the third filter is

A) 0
B) $I_0 / \sqrt{2}$
C) $I_0 / 2$
D) $I_0 / 4$
E) $I_0 / 8$
Clicker Question

The middle polarizing filter is then removed. What is now the intensity of the resulting light?

A) 0
B) $I_0 / \sqrt{2}$
C) $I_0 / 2$
D) $I_0 / 4$
E) $I_0 / 8$
Polarization in Reflection

• When light impinges on a surface, it generally partially refracts and partially reflects.
• The “plane of incidence” is the plane that contains the incident and reflected light rays.
• The electric field can be split into components: “p-polarization” in the plane of incidence, and “s-polarization” perpendicular to the plane of incidence.
• The efficiency of reflection is not the same for the two polarization components, so the reflected and transmitted beams are partially polarized.

① If unpolarized light is incident at the polarizing angle ...
② ... then the reflected light is 100% polarized perpendicular to the plane of incidence ...
③ ... and the transmitted light is partially polarized parallel to the plane of incidence.
④ Alternatively, if unpolarized light is incident on the reflecting surface at an angle other than θ_p, the reflected light is partially polarized.
Brewster's Angle

- The reflectivity for p-polarized light is exactly zero at a certain angle of incidence.
- This angle is called Brewster's angle.
- At Brewster's angle, the reflected and refracted rays are perpendicular.
- This behavior is described by the Fresnel equations mentioned before (derived from Maxwell's equations).
- For light incident from medium $a$ into medium $b$, Brewster's angle $\theta_p$ satisfies:

$$\tan(\theta_p) = \frac{n_b}{n_a}$$
Brewster’s Angle Applications

Note: This is a side view of the situation shown in Fig. 33.27.

Component perpendicular to plane of page

Reflected ray

Normal

$\theta_p$  $\theta_p$  $\theta_b$  $n_a$  $n_b$

Reflected ray

When light strikes a surface at the polarizing angle, the reflected and refracted rays are perpendicular to each other and

$$\tan \theta_p = \frac{n_b}{n_a}$$

- So-called “Brewster windows” are used inside lasers and other optical instruments where reflections must be completely eliminated.

- Sunlight reflected from horizontal surfaces has a large horizontal polarization, the glare of which can be largely eliminated with vertical polarizing sunglasses.
The other day, when I was spying on my neighbors, I was able to eliminate all glare by using a polarizer. Was my polarizer

a. Horizontal
b. Vertical
c. Right-circular
d. Left-circular
e. Elliptical?

without polarizer: glare from sky obscures inside

with polarizer: no glare, window glass invisible
Scattering of Light by Air

- The sky is blue because the scattering of light by air molecules is proportional to $1/\lambda^4$.
- Blue (450 nm) scatters more than red (750 nm) by a factor of $(750/450)^4 \approx 8$.
- The blue light from the sky is polarized in a direction perpendicular to the line toward the sun.
Birefringence

- Calcite is a crystal for which the index of refraction depends on the polarization of the light (birefringence).
- The light is refracted into two images, each polarized differently.
- Application: Make efficient polarizers!
Unpolarized light is incident on two ideal polarizers that are crossed at an angle of 60 degrees. Recall that \( \cos(60 \text{ deg}) = 1/2 \).

What fraction of incident light is transmitted through both polarizers?

a) 1/2.
b) 1/4.
c) 1/8.
d) 1/16.
e) It depends on whether the incident light is linearly or circularly unpolarized.