Physics 228

Exam next Sunday 2/28, 8:10 - 9:30 pm
Chapters 33-36

Today:

Polarization of Light
Light Scattering
Birefringence
Linear Polarization

Polarization refers to the orientation of the electric (and magnetic) fields of a light wave. For example,

\[ \vec{E}(z, t) = E_0 \cos(kz - \omega t) \hat{x} \]
\[ \vec{B}(z, t) = B_0 \cos(kz - \omega t) \hat{y} \]

But the orientation of the fields could be different:

\[ \vec{E}(z, t) = E_0 \cos(kz - \omega t) \hat{y} \]
\[ \vec{B}(z, t) = -B_0 \cos(kz - \omega t) \hat{x} \]

Or:

\[ \vec{E}(z, t) = E_0 \cos(kz - \omega t) \frac{\hat{x} + \hat{y}}{\sqrt{2}} \]
\[ \vec{B}(z, t) = B_0 \cos(kz - \omega t) \frac{\hat{y} - \hat{x}}{\sqrt{2}} \]

\( \vec{E} \) and \( \vec{B} \) are perpendicular, and perpendicular to the propagation direction (subject to right-hand rule).
Circular Polarization

“Right handed circular polarization”: As the light heads towards us, we see the fields rotating clockwise.

“Left-handed circular polarization”: As the light heads towards us, we see the fields rotating counter-clockwise.

Any direction of linearly polarized light can be represented as a sum of RH + LH circularly polarized light, and vice versa.
Elliptically polarized light may be “right-handed” (shown) or “left-handed”.

Unpolarized light: Polarization direction fluctuates randomly on a very fast timescale.
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

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

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

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”. 
Polarization of Light Sources

In a broadcast antenna, electrons oscillate vertically, producing vertically polarized radio waves. Watch simulation!

In an incandescent body (such as the sun, or a light bulb) there is no preferred direction. Thus most natural light is unpolarized.
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

Malus’s Law:

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

Crossed polarizers block all light!
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°, 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(\varphi_1-\varphi_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) $I_o / \sqrt{2}$
- C) $I_o / 2$
- D) $I_o / 4$
- E) $I_o / 8$
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 ...

4. Alternatively, if unpolarized light is incident on the reflecting surface at an angle other than $\theta_p$, the reflected light is partially polarized.

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.
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

• 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.
Brewster’s Angle iClicker

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

Unfortunately, nothing interesting can be seen here. 😞
(The other pictures I can’t show.)
Scattering of Light by Clouds

- Clouds consist of microscopic water droplets that scatter light.
- Thin clouds are white because they scatter all wavelengths equally.
- The bottom of thick clouds appears gray because much of the light is absorbed.
- The scattered light is unpolarized.
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.

Electric charges in air molecules at $O$ oscillate in the direction of the $E$ field of the incident light from the sun, acting as antennas that produce scattered light. The scattered light that reaches the observer directly below $O$ is polarized in the $z$-direction.

Air molecules scatter blue light more effectively than red light; we see the sky overhead by scattered light, so it looks blue.

This observer sees reddened sunlight because most of the blue light has been scattered out.
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 $\cos(60\degree) = 1/2$.

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.