Experiment 5: Polarization and Interference

PHYS C1493/C1494/C2699
Introduction

- Quick review on *electromagnetic waves*.
- **Polarization** of Electromagnetic waves.
- **Interference** of Electromagnetic waves.
  - Young's double slit experiment
- **Diffraction** of EM waves
Electromagnetic waves

- In more detail:
  - Oscillating electric (red) and magnetic field (gold).
  - Electric field and magnetic field are perpendicular to each other.
Polarization of light wave

- **Polarization of light wave**: vibration axis of electric field

- Light is usually *unpolarized*; all directions of the electric field are *equally probable*.

- **Linearly polarized light**: vibrates in the same direction at all times at a particular point in space.

Unpolarized beam of light moving out of the screen. All directions are equally probable

Linearly polarized beam of light moving out of the screen. Electric field points in one direction only.
Polarization by selective absorption

- White light is usually **unpolarized**: Electric field is not emitted in a preferred direction.
- Possible to polarize light through polarizing filter
- Certain materials will absorb electric fields in a **preferred direction**! We can use this to polarize a beam.
Malus's Law

- So what do we observe when we see light?
  - Oscillating electric field? No.
  - Your eyes observe the intensity \( I \).

- **Intensity**: Roughly speaking, it is the *time average* (RMS) of the oscillating electric field.

- If we place two polarizers in sequence, the intensity of the transmitted polarized light will depend on the orientation of the angle between polarizers.

\[
|\vec{E}_{\text{trans}}| = |\vec{E}_o| \cos(\theta)
\]

- Electric field of light coming out of second polarizer
- Electric field coming out of first polarizer
Malus's Law

- Intensity of transmitted light through two polarizers:

\[ I = |\vec{E}_{\text{trans}}|^2 = |\vec{E}_o \cos(\theta)|^2 \]

\[ = |\vec{E}_o|^2 \cos^2(\theta) \]

\[ = I_o \cos^2(\theta) \]

- This is **Malus's Law**:

\[ I = I_o \cos^2(\theta) \]
Young's double slit experiment

In what other way do we know about the wave nature of light?

Young's double-slit experiment (1801):

- Pass light through two very narrow slits and observe pattern on distant screen.
- Waves interfere creating a fringe pattern of light and dark spots.
Young's double slit experiment

- Can be derived with physical optics. Two rays interfere at a point on the screen.

Peaks are bright spots

Valleys are dark spots
Condition for a bright spot

- Let the screen be at a distance $D$ which is much larger than the distance between slits ($d$).
- Rays emerge almost parallel to each other.
- One of the rays has a slightly longer path length given by:

$$\Delta l = d \sin(\theta)$$
Condition for a bright spot

- Now we can predict the position for a bright spot (maximum)
  \[ \Delta l = d \sin(\theta) = m\lambda \]
  where "\( m \)" is an integer and \( \lambda \) is the wavelength of light.

- In other words, light has to have the condition of traveling a path length of a full wavelength in order to constructively interfere.

- Using small angle approximation:
  \[ \sin(\theta) \approx \tan(\theta) = \frac{x_m}{D} \]

Predict distance \( x_m \) to observe bright spot:
\[ x_m = m \left( \frac{\lambda D}{d} \right) \]
Young's double-slit experiment

- Just explained the *interference effects* from the double slit.
- However, in reality you will observe a combination of effects: *Interference and diffraction effects*
Young's double-slit experiment

- Just explained the **interference effects** from the double slit.

- However, in reality you will observe a combination of effects: **Interference and diffraction effects**

- **Diffraction**: Spread of waves around an obstacle

- Wave behaves as though it were interfering with itself.

*FIGURE 36-4* The diffraction of water waves in a ripple tank. Waves moving from left to right flare out through an opening in a barrier along the water surface.
Diffraction intensity pattern

- The intensity pattern follows the following relation:

\[ I = I_o \left( \frac{\sin \left( \pi \frac{a \sin \theta}{\lambda} \right)}{\pi \frac{a \sin \theta}{\lambda}} \right)^2 \]
Diffraction intensity pattern

- The intensity pattern follows the following relation:

\[ I = I_o \left( \frac{\sin(\pi a \sin \theta / \lambda)}{\pi a \sin \theta / \lambda} \right)^2 \]

- Single-slit *minima* occur at:

\[ \frac{\pi a \sin \theta}{\lambda} = n \pi \]

\[ n = \pm 1, \pm 2, \ldots \]

\[ a = \text{single-slit width} \]

- Again using small angle approximation:

\[ x_n = \left( \frac{\lambda D}{a} \right)^2 n \]
The Experiment
Procedures

- Measuring the polarization properties of EM waves
  - Polarize beam of white light.
  - Verify **Malus' Law**: Measure intensity of white light when light travels through two polarizers at an angle $\theta$ with respect to each other:
    \[ I(\theta) = I_o \cos^2(\theta) \]

- Young's double-slit experiment (Interference)
  - Use He-Ne laser as coherent light source
  - Determine wavelength $\lambda$ from double-slit *interference* pattern
  - Determine wavelength $\lambda$ from single-slit *diffraction* pattern
Equipment

- Linear Translator
- Holders
- Incandescent Light Source
- Photometer
- Fiberoptic Cable
- Incandescent Light Source Power Cord
- Polarization Filters (18 and 19)
- Red Filter (32)
- Slit Accessory Slide (13)
- Bench Couplers and Screws
Polarization of light

- **Equipment:**
  - Incandescent light source (source of EM waves)
  - Polarization filters
  - Photometer (measures intensity of outgoing EM waves)

- **For polarization:**
  - Incandescent light is a source of **unpolarized** EM waves
    - E-field has no preferred direction
  - Place a polarizer in front of the incandescent light source

Outgoing light should be polarized!

Fig.1  Polarization of light
Malus's Law

- Polarizers in sequence
  - Place two polarizers in front of the light source
- Measuring intensity of light:
  - Align the axis of both polarizers such that they are parallel to each other. Measure and record intensity.
  - Rotate one of the polarizers in 5-10 degree increments with respect to other polarizer. Record intensity

![Diagram of Malus's Law](image)
Analysis of Malus' Law

- Malus Law Hypothesis:
  \[ I = I_o \cos^2(\theta) \]
- Linearize data by plotting relative intensity vs. \(\cos^2(\theta)\)
- Plot residuals to check for systematic effects.
Young's double-slit experiment

- **Procedure:**
  - Mount laser in far end of optical bench.
  - Mount slit set C (double-slit) in front of the laser beam.
  - Observe double-slit intensity pattern with a white piece of paper.
  - Use *linear translator with fiber optic* attached to measure intensity at different positions in the transverse direction.
Analysis: double-slit experiment

- Plot $x_m$ vs. order number
- Perform a linear fit.
- Use slope to estimate wavelength of the laser.
  - Remember to propagate uncertainties.
- Results can be accurate if you're careful:

  $\lambda_{\text{meas}} = 626.1 \pm 3.5 \text{ nm}$

  $\lambda_{\text{theor}} = 632.8 \text{ nm}$
Analysis: single-slit envelope

- Once again take measurements in the transverse direction but in smaller increments.
- Plot relative intensity \( \left( \frac{I}{I_o} \right) \) vs. order number \( m \).
- Should be able to observe the single-slit envelope.
- Using the **single-slit width** \( a \), determine wavelength of laser.

\[
I = I_o \left( \frac{\sin \left( \frac{\pi a \sin \theta}{\lambda} \right)}{\pi a \sin \theta / \lambda} \right)^2
\]
Summary

• Observed wave-like properties of light
  • Malus's Law
    – Polarization
  • Young's double slit experiment
    – Interference
    – Diffraction

• Able to measure the wavelength of He-Ne laser.