

WAVES-B

Polarization of Light & Michelson Interferometer

revised August, 2021

(You will do two experiments; this one and the WAVES-A experiment. Sections will switch rooms and experiments half-way through the lab.)

Learning Objectives:

During this lab, you will

1. estimate the uncertainty in directly measured quantities.
2. fit a cosine-squared model to a set of experimental data.
3. study polarization of light.
4. determine the wavelength of light from a laser using a Michelson interferometer.

A. Introduction

For Labs 7A and 7B you are to submit to Canvas one worksheet worth 30 points before you leave class. No paper is required.

This laboratory experiment includes studies of polarization effects as well as measurements of interference with the Michelson Interferometer. You should have read the *Introduction* and *Theory* sections of WAVES-A before proceeding with these measurements.

The direction in which the electric field vector of an electromagnetic, EM, wave points as the EM travels through space is called its direction of polarization. This polarization direction must be perpendicular to the direction of travel. Light from most natural and artificial sources is unpolarized; the electric field vector is randomly oriented in a plane perpendicular to the direction of

propagation of the wave. Unpolarized light can be polarized by passing it through a sheet of polarizing material which absorbs one component of the light and allows the other to pass. The component which is along the polarizer's *axis of polarization* passes through the polarizer.

There are many natural materials that at least partially polarize light, particularly reflected light. Almost any shiny surface, such as flat water, works well. At a particular angle of reflection, called the Brewster angle, the reflected light is completely polarized parallel to the reflecting plane. The reflecting plane is defined by two lines, one along the direction of propagation of the incident beam of light and the other normal to the reflecting surface. A specularly reflected beam will also move in a direction contained in this plane. So at the Brewster angle, the electric field vector of the reflected light also lies in this plane, although it is still perpendicular to the direction of travel of the reflected beam.

It will be more convenient in most of our experiments to use an artificial material, Polaroid, invented by Edwin Land, who also invented the Polaroid Camera. This is the same material that gives Polaroid sunglasses their ability to reduce glare. Glare, which results when sunlight is reflected from a highway, car hood, water, etc., is highly polarized and is usually reflected from a horizontal surface. The Polaroid film in sunglasses can preferentially remove this glare while letting other light pass.

The ability of some materials to polarize light depends upon the peculiar optical properties of certain molecules and crystals, and in the case of Polaroid, upon the properties of stretched sheets of plastic (polyvinyl alcohol). Stretching this plastic causes the molecules to line up parallel to each other and gives them optical properties that depend on the direction of light relative to the film. A

sheet of this polarizing material can be used as an *analyzer* to study the properties of polarized light.

B. Apparatus

There are three major experiments in this lab, described in parts C (*polarization by transmission*), D (*polarization by reflection*) and E (*Michelson interferometer*). Three or four lab stations are set up for parts C and E. Measurements for part D are taken in the hallway outside the lab; two groups at a time may do this. Which experiment you do first depends on where you are sitting at the beginning of the lab session.

For part C, you will use three Polaroid slides as well as a fixed and a rotatable polarizer mounted above a light sensor. Part D requires a large sheet of Polaroid film, a 2 meter stick and a light bulb. Part E is an interference experiment rather than a polarization experiment and requires a Michelson Interferometer and a diode laser. The wavelength emitted by these diode lasers is close to that of the red light emitted by standard He-Ne lasers; it should be in the neighborhood of 635 nm.

C. Polarization by Transmission

C.1. Theory

To understand how polarizers work, we must first have a model for transmission of light through materials and reflection from surfaces. It is only necessary to consider the electric field vector; you may ignore the associated magnetic field. We “see” when the electric field of an electromagnetic wave of suitable frequency strikes our retina and causes its electrons to vibrate. Similarly, when light strikes any medium, the electric field may set up vibrations in the material which will itself radiate and pass on the transmitted and/or reflected beam.

A polarizing sheet consists of arrays of linear conductors, indicated by the horizontal and vertical lines on the two polarizers illustrated in Fig. 1b and 1c. Fig. 1a represents a plane perpendicular to the direction of travel of an EM wave. The vector in this figure is aligned with the electric field vector of the EM wave, showing the original direction of polarization. When this wave strikes the polarizer (1b), its electric vector \vec{E} excites electrons in the plane of the polarizer. The *polarization axis* is defined as the axis which passes light and is represented by the \uparrow on the polarizer. The linear conductors inside this polarizer are aligned in the x -direction, as illustrated, and the component E_x sets the electrons in the conductors into oscillation along the conductors so that they dissipate the energy as heat (I^2R losses). The component E_y , which is perpendicular to the linear conductors loses relatively little energy to conduction electrons, so this field passes through the polarizer.

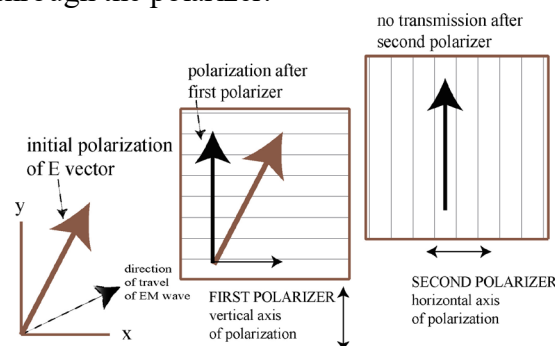


Figure 1: Two crossed polarizers.

If the incident direction of polarization of the light makes an angle θ with the axis of polarization, the component $E \cos \theta$ will be transmitted through the polarizer and the resulting intensity of the light will be proportional to $\cos^2 \theta$ (since intensity is proportional to the square of the amplitude). Unpolarized light consists of a random mixture with \vec{E} -vectors vibrating in all directions

perpendicular to the direction of propagation. If unpolarized light were to strike polarizer (1b), only the y -component of each \vec{E} -vector would survive, resulting in light polarized in the y -direction as illustrated by the vector in Fig. 1c.

The effect of a second, *crossed* polarizer is also illustrated in Figure 1. Note that, since the first polarizer passes only E_y and the polarization axis of the second polarizer is along x , no light passes polarizer (1c).

C.2. Qualitative Measurements

You should have 3 Polaroid slides at your station. **Look directly at a light source (not a laser!) through one of them. Rotate the polarizer.** Nothing much should happen. **Add a second polarizer. Keep one at a fixed angle while you rotate the other through at least 90° and look at the light.** What happens now?

Cross the two polarizers so that no light is transmitted. Now insert a third polarizer *between* the pair at an angle of 45° while observing the light source. What happens now? What happens if you place the third polarizer in front of or behind the two crossed polarizers rather than between them?

This experiment would be very difficult to explain if you didn't know that light behaves like a vector. A vertically polarized wave has no component in the horizontal direction so in the first experiment no light makes it past the second polarizer. However a vertically polarized wave does have a component at 45° and a wave polarized at 45° has a horizontal component. So some light does make it through in the second arrangement. In fact, if we inserted a lot of polarizers between the first two, each rotated slightly with respect to the one before it, we could shift the polarization continuously with very little loss of intensity after the first polarizer.

C.3. Quantitative Measurements

Examine the two polarizers which are mounted on the *LoggerPro* light sensor and observe how to change the light transmission by rotating one polarizer relative to the other. The sensor should be plugged into Channel 1 of the LabPro™ box with the switch on the light sensor box set to 600 Lux. **Load the *LoggerPro* program and open the experiment C:\Program Files \Vernier Software \LoggerPro3 \Experiments _E and M Labs \WAVES.** (If the default folder hasn't been changed, you should be in the Experiments folder when you go to the Open command.)

Start the *LoggerPro* program and observe the illumination readings as you rotate the top polarizer slowly from 0° through 360° (i.e., so that the intensity of the light varies through its maximum and minimum values over 10 - 20 seconds). **Stop the *LoggerPro* program and observe the illumination vs. time plot.** After the trial, the autoscaling feature of the program should set the scale so that you can view the entire illumination range on the monitor.

Now **set the top polarizer near the point that gives the maximum reading, using this as your 0° reference for the rest of this experiment, and start *LoggerPro*.** You'd expect a constant reading, but if you move around near the setup you will probably see significant changes. Try standing up, looking at your angle settings, moving your hand around near the polarizers and then sitting back down again. You will probably see significant changes in the signal. This is due to your blocking light or adding more reflections. It demonstrates the need to remove human presence during the readings. When you take the more careful measurements described in the next paragraph, sit or move a meter or so away

from the sensor while reading the light output at each plateau.

With the top polarizer set at the 0° mark, **start the *LoggerPro* program and let it run for 5-7 s. Then, without stopping the program, rotate the polarizer to 30° and again wait for 5-7 s. Repeat until you have reached 360°.**

Use your mouse to define a *region of interest* at each plateau, exploiting *LoggerPro*'s ANALYSIS/ STATISTICS function to **get the average value and error estimate of each region.** Your objective is to **make quantitative measurements of light intensity as a function of angle and to compare them to the theoretical prediction,**

$$I = I_0 \cos^2(\theta + \phi) + A, \quad (1)$$

where I_0 is the maximum intensity at $\theta + \phi = 0$, ϕ is a phase term and A allows for an offset in the detector.

C.4. Analysis

In *Origin*, plot the intensity I versus the angle θ . Make a least-squares fit to Eq. 1, entering the equation as:

$$I_0 * (\cos(x + P))^2 + A$$

Before proceeding with your fit, it is important to decide whether you will use radians or degrees for your units of angle. Most likely you will have taken and plotted your data in degrees. To force *Origin* to use a particular unit, go to TOOLS → OPTIONS → NUMERIC FORMAT and select DEGREES or RADIANS. (If you need a reminder how to do least squares fit, see the Appendix to this lab.)

D. Polarization by Reflection:

Brewster's Angle

D.1. Theory

You may have heard of the *index of refraction* n in the context of Snell's Law.

Snell's Law describes how light bends when it moves from one medium into another, say from water into air. This bending is what makes it difficult to pick up an underwater object when you are watching from above the surface – it's not where it appears to be. A larger index of refraction corresponds to a larger bend angle.

The same index of refraction appears in the formula for how the speed of light varies in different media. The speed of light in a material is just c/n or $(3 \times 10^8 \text{ m/s})/n$. The experiment that you are about to do lets you determine n for any reflective surface. So, armed only with a sheet of polarizer (or even a pair of Polaroid sunglasses), a meter stick and a light bulb, you can measure the index of refraction of anything!

Figure 2 illustrates polarization by reflection. When an incident ray (ab) strikes the horizontal surface at an angle θ to the normal, part of the ray penetrates and propagates at the angle θ' within the material as a refracted ray (bc), where the angles are related by Snell's law. The refracted ray sets the electrons in the surface into oscillation in a plane perpendicular to the ray. The oscillating electrons produce an electromagnetic wave which is perpendicular to the refracted ray and therefore can be decomposed into a component which lies in the plane of the surface, (*into the page, represented as \otimes*) and a perpendicular component (represented as \leftrightarrow).

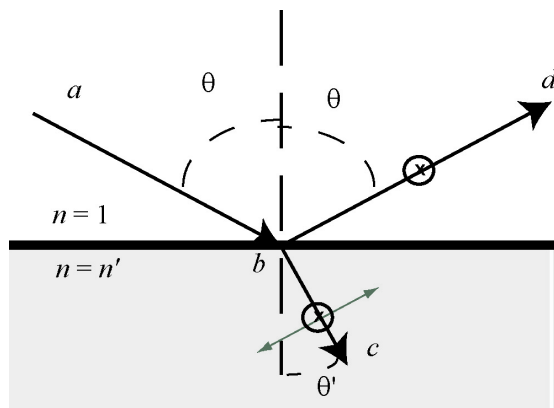


Figure 2: Illustration of Brewster's angle.

In a plane electromagnetic wave, the electric vector is always perpendicular to the direction of propagation of the wave. Thus, if the perpendicular component is along the direction of propagation of the reflected ray (*as illustrated*), then that component cannot propagate; only the component parallel to the surface can propagate and the reflected ray (*bd*) will be polarized parallel to the reflecting surface (*i.e., along* ⊗).

This condition for total polarization is

$$\pi - (\theta + \theta) = \pi/2 \text{ or } \theta + \theta = \pi/2$$

so $\theta = \pi/2 - \theta.$

Snell's law gives

$$n'\sin\theta = n\sin\theta \text{ or } n'\sin\theta = \sin\theta$$

where $n=1$ is the index of refraction of air and n' is the index of refraction of the dielectric material. Therefore,

$$n'\sin(\pi/2 - \theta) = \sin\theta \text{ or } n'\cos\theta = \sin\theta$$

so $\tan\theta = n'. \quad (2)$

Thus, you can determine the index of refraction by measuring the angle at which the reflected ray is completely polarized.

D.2. Qualitative Measurements

Go to the glass next to the lab door and stand near the door handle so that you can see through the glass at an angle into the hall and also see a reflection of objects in the room (*the computer monitors are usually easy to see*). Now look through one of the large sheets of polarizer kept near the door and begin rotating the sheet. With one orientation, you will see no effect except for a darkening but if you then rotate the polarizer 90° you should be able to almost cut out the reflections of objects in the room and make it easier to see through the glass into the hall. This is the effect you are about to measure more carefully. It is also exactly what a pair of Polaroid sunglasses would do for you, removing the glare from reflections.

D.3. Quantitative Measurements

The measurement you need to make in the hallway outside the lab is illustrated in Fig. 3. Each partner should have a sheet of polarizer. Note the bare light bulb and its reflection in the floor. **Stand next to each other approximately 3 m from the bulb and look through the polarizer at the bulb=s reflection. Rotate the polarizer until the reflected light has minimum intensity.**

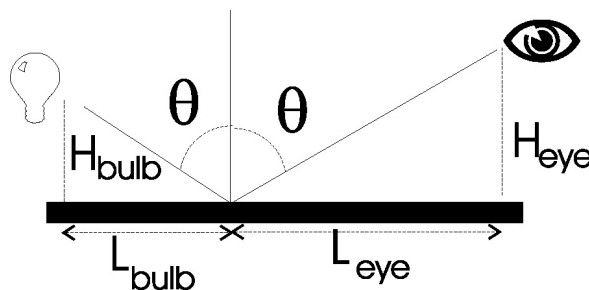


Figure 3: Measuring Brewster's angle.

Walk towards and away from the bulb while watching the reflection through the polarizer and find the spot at which you must stand so that the reflection most completely disappears when blocked by the polarizer. Check by rotating the polarizer

while taking a step towards and a step away from this position.

When you and your partner(s) have found this position (*you may disagree on the position if you differ in height but you should agree on the angle*), **one of you (the Boss) should stay there and direct your partner (the Peon) in marking the spot on the floor where you see the reflection. Place a rubber stopper or some other small object on this spot.** The Boss must remain in position while the Peon measures the height of the Boss' eye above the floor and distance from the marker. One partner should then measure the height of the bulb above the floor and its distance from the marker. Remember to record estimates of uncertainties as well.

D.4. Analysis

Calculate the tangent of the angle of reflection for both the incident and reflected light. They should be the same. If they differ slightly, average the two; if they differ by a considerable amount, re-measure. You should also calculate the angles themselves but these are not needed for the analysis. Calculate the index of refraction of the floor tiles (or floor wax) from your measurement of the Brewster angle and Eq. 2. (*One should expect to find an n' that is greater than 1. If you find a number less than 1, you have discovered that floor wax supports warp speeds and you will soon be awarded a Nobel Prize in Physics—or you made a mistake. Check if you used the wrong angle in your calculation, switching L and H in Fig. 3.)*)

E. The Michelson Interferometer

E.1. Background and Theory

The Michelson interferometer was invented by Albert Michelson, the first Professor of Physics (1883) at Case School of Applied Science and the first American to win the Nobel Prize in Physics (1907). He is remembered best for his famous experiment

with Edward Morley, Professor of Chemistry at Western Reserve University, which showed that the velocity of light is independent of the velocity of the reference frame in which it is observed. This is one of the cornerstones of Einstein's theory of relativity.

Michelson obtained two coherent beams for the investigation of interference effects with a *beam splitter*, a partially silvered mirror which separated the beam along two mutually perpendicular paths. The two beams were later merged along a common path to reveal the interference effects. A model of the interferometer used by Michelson for his famous ether drift experiment has been set up in the Rockefeller Building lobby.

Figure 4 shows a schematic diagram of the light paths through the lab interferometers. A photograph on the lab web site shows the actual interferometer you will use, including labeling of its major parts. Note the beam splitter mirror in the center of the apparatus and the two totally reflecting mirrors which are used to combine the two beams. By adjusting the micrometer that controls the position of the movable mirror, we can change the difference between the two light paths. We will make no attempt to obtain equal paths; we are only interested in measuring changes in the path difference. Since the light reflects from the movable mirror, changing the position of this mirror by Δd changes the path difference $2\Delta d$ (since the light must travel to the mirror and then back again). Thus, if you move the mirror by 10 wavelengths, you should observe 20 interference maxima.

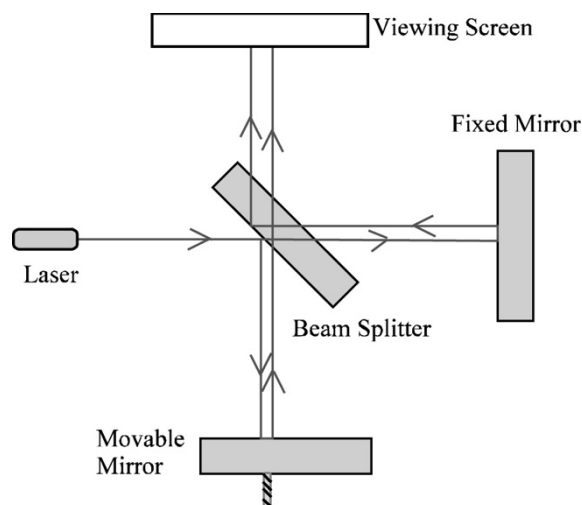


Figure 4: Michelson interferometer.

E.2. Measurements

Do not move the laser or any part of the Michelson interferometer except the micrometer! (The micrometer is the calibrated knob on the side of the interferometer. There are tick marks in micrometers for taking precise measurements.) The interferometer is delicate, can easily fall out of alignment and may take some time to realign. Ask for help if there are any problems, especially if your group is having trouble seeing the circular fringes.

Examine the interferometer and be sure that you understand the light path. **Turn on the laser** if it is off but do not attempt to adjust it. (The laser runs from the fixed 5 volt output of an Elenco power supply. Rotate the power knob on the right side of this power supply clockwise to turn it on - it doesn't matter how far you turn it past its clickstop.)

Note the circular fringe pattern projected on the viewing screen. This screen is just a wall or the side of a computer monitor. You may if you wish tape a piece of paper to the surface on which you project the fringes and make markings on this paper to help you in your counting.

To prove that you are seeing interference of two beams, **block one of them by**

carefully placing a finger or piece of paper in one or the other of the beam paths, between the beam splitter and each of the mirrors. The fringe pattern will disappear although the screen will still be illuminated through the other path.

Before you begin counting, turn the calibrated knob on the movable mirror at least one full turn counter-clockwise, stopping when the zero on the knob is aligned with the index mark. Then continue to rotate the knob slowly counter-clockwise as you count the fringes moving past a fixed point on the screen. (By rotating the knob in one direction only, you reduce the effects of backlash or play in the screw. Be careful though, if the previous group didn't return the screw to the proper position, you could back the screw off of its threads and have it fall off in your hands.) **Count at least 50 fringes. Stop turning the screw, but continue to watch the image once you have stopped turning the micrometer it may drift for a few extra seconds and the micrometer settles into equilibrium. Continue counting these extra fringes until the image is stable and has stopped moving. Then record the total fringe count N and the micrometer screw reading Δd (in μm).** You must concentrate carefully while counting fringes. It is easy to let one or more slip past unnoticed if your mind begins to wander.

After you have recorded the reading of the micrometer screw, **return the screw to its original position** so that the instrument is ready for the next group.

E.3. Analysis

Calculate the wavelength of the light from your measurements. The scale on the adjustment screw reads in microns (10^{-6} m). The equation that you need to use is $\lambda = 2\Delta d/N$ where the 2 comes from the fact that the path is traveled by the light going and coming from the moving mirror, Δd is the

distance you move the mirror with the micrometer and N is the number of fringes that you count, which should be about $N = 50$.

Estimate the uncertainty in your value in λ .

Check that your answer is consistent with the wavelength of visible light from a laser. Repeat the measurements more carefully if necessary.

F. Holograms

The hologram is another example of a practical application of the theory of the interference of light. By recording the intensity variations produced by interference between a reference beam and monochrome light reflected from an object, the hologram-maker is able to store in photographic film a record of the relative phases of the light reflected from the object to the film. Passing light back through the developed film then allows an accurate three-dimensional reproduction of the original object.

There are several holograms available in the laboratory for your examination, both transmission and reflection types. Your instructor will assist you in observing and understanding them.

Appendix. Least-Squares Fit

The equation that you need to fit, Eq. 1, will be typed into *Origin* as:

$$I_0 * (\cos(x + P))^2 + A$$

It should be clear how I_0 , P , and A relate to the variables used in Eq. 1. The steps in carrying out the fit are:

1. Plot your data
2. Select ANALYSIS → FITTING → NON-LINEAR CURVE FIT → OPEN DIALOG

3. Click on the NEW button (next to Add under Function)

4. Name your function and select the EXPRESSION Function Type.

5. Type " I_0 , P , A " into PARAMETER NAMES

6. Type in your initial estimates of the fitting variables I_0 , P , and A . You should be able to make these estimates yourself, without a calculator, with a basic understanding of the shape of a cosine curve. Simply examine the data on your plot and decide what values correspond to I_0 or I_0 , ϕ or P , and A or A .

Then type in your expression:

$$y = I_0 * (\cos(x + P))^2 + A$$

Press Next and then Finish

8. Press 1 or 100 ITER (*iterations*) and pray that Origin's fitting routine works. If the initial fit is far off, the problem may be with the values you used for initializing the three variables. You can check this by going to the "Residual" tab, changing your Parameter values under the "Parameters" Tab and pressing the SIMPLEX button (Icon has an arrow going counter-clockwise with an "S")
9. When you are satisfied with the fit, press FIT.