Polarization Rotation DC
Rochester Institute of Technology

PHYS-316 Advanced Lab*

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Goals

The historically-named 'Faraday effect' refers to a rotation of the plane of polarization of light as it passes through a material in the presence of a magnetic field pointing along the light's propagation direction. Discovered in 1845, it was the first demonstration of the "magnetic" part of electromagnetic radiation. This polarization rotation is a very small effect. In this lab, the angle of rotation is measured first in a DC magnetic field, and later in an AC magnetic field using a lock-in amplifier for phase-sensitive detection.

Introduction

During the 1830's, Michael Faraday became convinced that because electric currents produce magnetic fields, the reverse should also be true, and magnetism should somehow be able to produce electricity. Eventually his experiments succeeded, and Faraday's law, as you studied it in University Physics, was demonstrated. Thus electrical and magnetic phenomena were linked.

Some years later, Faraday became convinced that light was an electromagnetic phenomena of some sort, and that the presence of an electric or magnetic field "should" influence the light. Having already demonstrated the interplay between electricity and magnetism, Faraday believed that all of optics were also electro-magnetic phenomena! There was little to no theoretical basis for such a belief at the time, but a young theorist (later named Lord Kelvin) encouraged the notion. In August of 1845 Faraday succeeded in demonstrating that the passage of light through matter was influenced by a magnetic field.

From Michael Faraday's notebook on Sept. 13th 1845: "A piece of heavy glass was 2 inches by 1.8 inches by 0.5 of an inch thick, being silico borate of lead, and polished on the two shortest edges, was experimented with. It gave no effects when the same magnetic poles or the contrary magnetic poles were on opposite sides (as respects the coarse of the polarized ray) - BUT, when contrary magnetic poles were on the same side, there was an effect produced on the polarized ray, and thus the magnetic force and light were proved to have relation to each other. This fact will most likely prove exceedingly fertile and of great value in the investigation of both conditions and natural force."

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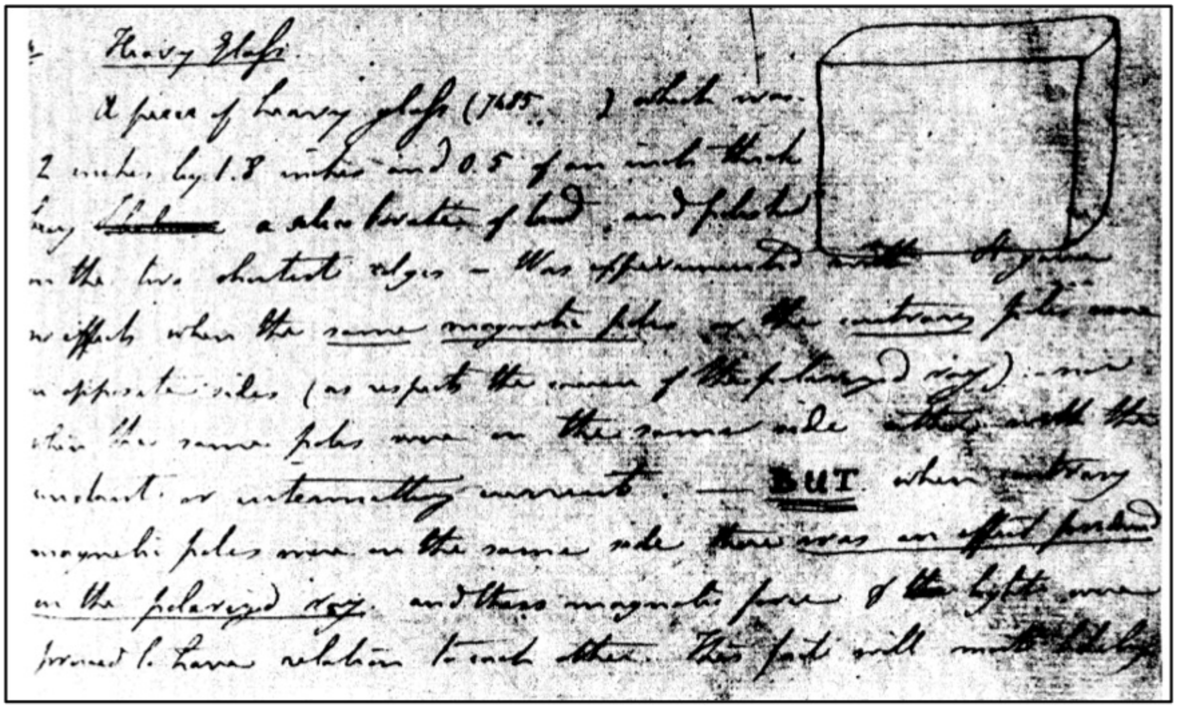

Heavy Glass.
A piece of heavy glass (7685) which was
2 inches by 1.8 inches and 0.5 of an inch thick
being a silico borate of lead, and polished
on the two shortest edges – Was experimented with. It gave
no effects when the same magnetic poles or the contrary poles were
on opposite sides (as respects the course of the polarized ray) – nor
when the same poles were on the same side either with the
constant or intermitting current. — BUT when contrary
magnetic poles were on the same side there was an effect produced
on the polarized ray, and thus magnetic force & the light were
proved to have relation to each other. This fact will most likely

Figure 1: Faraday's notebook entry from when he discovered the effect.

This result was the first confirmation of the electromagnetic nature of light, and the first indication that optical properties of a material are a result of electromagnetic interactions within the material. It is a very small effect and rather difficult to observe even with modern laboratory equipment. Faraday's discovery of such a small effect, using such primitive equipment, with little more than intuition to encourage his explorations, remains a remarkable achievement.

The Faraday Effect finds practical application in modern optical isolators used for fiber optic communication systems. It is also used in optical modulators, and the measurement of Verdet constants (which characterize the strength of the effect in different materials) is an important analytical tool in chemistry.

In this lab, you will measure the 'Faraday Effect' in a piece of glass using two techniques. The DC measurement is straightforward to understand but limited by the small size of the effect. The AC technique uses phase sensitive detection with a lock-in amplifier, which is somewhat more difficult to understand and set up, but allows for the accurate measurement of extremely tiny signal with great precision. Lock-in measurement techniques are of great significance in research physics; the technique itself merits careful attention.

Theory

Faraday discovered that when plane polarized light passes through a material, with a magnetic field along the direction of propagation of the light, the plane of polarization rotates. The change in the angle of polarization $\Delta\theta$ is related to the strength of the magnetic field B, the length of the sample L, and the Verdet constant ν (a property of the material) by

$$\Delta\theta = BL\nu \quad (1)$$

A full explanation of the Verdet constant ν requires a detailed knowledge of the material structure and some quantum mechanics. Suffice it to say that ν is generally very small, and depends, both in sign and in magnitude, on the material. This is why a measurement of ν is a useful analytical tool, particularly when characterizing hydrocarbon chemicals.

Despite its simplicity, Equation 1 is a complete description of the Faraday Effect. In order to obtain a measurable rotation, a long sample and/or a strong field is needed. Even with these, if the Verdet constant ν for the material of interest is unusually small, the effect will be difficult to observe.

If the experiment is done with a DC field, Equation 1 is all that is necessary.

Equipment

Figure 2: The basic components of the Faraday rotation apparatus. The optical path goes right to left.

Light Source: A red diode laser is used as the light source. It operates at a nominal wavelength of about 650 nm, and power of approximately 3 mW. There is a polarizing filter at the output of the laser to ensure that the light is at least 95% polarized.

The laser requires a 4 Vdc power source to operate, provided on the back of the audio amplifier. For the DC part of the experiment, the audio amplifier is not used but the laser power source is. **Do not reverse the leads - doing so will destroy the laser!** When you must insert or remove the glass rod from the solenoid, remove the laser mount from the underside of the wooden stand using the Allen wrench.

Solenoid Magnet: The solenoid used to provide the magnetic field has the properties discussed in the pre-lab.

Analyzer: The analyzer polarizer is mounted in a precision ThorLabs rotation mount. Do not remove it from its mount.

Detector: The detector is a simple photodiode connected in series with one of three resistors (1 kΩ, 3 kΩ, or 10 kΩ). The resistor selection switch is tiny and mounted on the front of the photodiode unit. The photodiode is a current source and its output is linear with incident optical intensity, so long as the voltage across it is less than about 0.3 V. Saturation occurs at about this voltage and the device is no longer a linear detector. Be sure that your optical output signals do not reach 0.3 V at the detector; if so, you need to change to a different resistance setting. **In general, the 3 kΩ setting is effective.**

Sample: The sample is a 10-cm long glass rod, made of SF-59 flint glass. Its large Verdet constant is known to be $\nu = 0.0013$ degrees/Gauss-cm. The ends are highly polished and should not be touched or scratched. The sample is either inside the solenoid or stored in a box nearby.

Set-up and Calibration

Identify each of the parts listed above. Find the sample; it may be within the solenoid, or it may be in a box on the bench. Leave the laser connected to the power supply at the back of the audio amp; the amp is simply unplugged to turn the laser off.

Remove the laser from the wooden stand so that you can remove the glass sample. Use the flexible cable tie as a push-rod to gently push the sample out from the other end of the solenoid. Store the sample safely.

1. Measure and record the resistance of the solenoid coil with a handheld multimeter.

2. Calibrate the magnetic field strength as a function of current, with the probe fixed at the center of the solenoid ($z = 0$). Use a DC power supply to the magnet coil and calibrate over the range ± 4 Amps DC. Put an ammeter in line with the coil to measure the current. Do not leave currents of more than 1 Amp running into this coil for very long. It is best to begin taking data at a high magnitude of current and work down to zero current, to prevent overheating.

3. At a fixed 1-Amp current, measure field strength as a function of z-position over the full length of the solenoid. Repeat the same z-scan with the current leads reversed. By what percentage does the field magnitude vary over the length of the glass sample (when it is centered in the solenoid)?

4. Set the field to zero, and carefully insert the sample and make sure it is centered within the solenoid. Reassemble the laser, and align.

Measurement of Malus' Law

Place the glass rod at the exact center of the solenoid, if it is not already in place. Observe the output from the photodiode with a **Keithley microvoltmeter** reading DC volts.

Examine the analyzer polarizer. You can easily read the position within one degree from the front.

As shown in Figure 3, there is a locking screw on the lower side of the polarizer mount. When it is loosened, the polarizer can be manually rotated within the mount. Do so, and observe how the signal changes. Note that the locking screw only locks this coarse adjustment; the fine adjust works even with it locked.

The fine adjust knob at the top allows very precise adjustment of angle. Convince yourself that one full revolution (25 tics) corresponds to one degree.

Figure 3: Location of the fine adjust and locking screw on the analyzer mount.

With the locking screw unlocked, rotate the polarizer manually and find the signal strength at the two maxima and two minima. You should have a signal of around 0.2 V at the maximum; if it is much smaller, your optical path is poorly aligned.

If your maximum signal is 0.3 V or more then you need to change the resistance setting on the photodiode; its output is "clipping" and you are not getting a good sinusoidal Malus curve.

Record the signal across the entire range 0 to 360 degrees in increments of your choosing. Do a quick Excel plot (or manual plot) of the voltage as a function of angle to be sure that the detector is not saturated. You will analyze this data in more detail later.

DC measurement of polarization rotation

Set the fine adjust knob to midrange (1.00). Now you have 4 degrees of range in either direction, with each degree divided up into 25 subdivisions. Make sure you can read the dial correctly.

Manually set the polarizer so that you are at complete extinction, a minimum near zero. You must determine if room lights are impacting your signal, and work under a black cloth if necessary. Lock the locking screw (you can use the fine adjust even with the locking screw tight). You have now set up the optics for good extinction, at zero field.

When you turn on the current, the 'Faraday effect' will change the polarization of light at the output; you will measure the analyzer angle using the fine adjust to re-zero the signal. This change in angle $\Delta\theta$ is the rotation of the polarization axis.

Record the rotation angle $\Delta\theta$ as a function of current. Begin at the highest current, and work your way down to zero. At zero current, switch the leads to the magnet coil and repeat the measurement for negative fields.

Analysis

Plot the field calibration data, B as a function of current I. Find the slope with uncertainty. Use this to convert all of your current readings to field strength in Gauss, with uncertainty.

Plot the magnetic field magnitude (average your measurements for positive and negative current) as a function of position z and mark on your graph the range of positions occupied by the sample.

Fit the appropriate functional form to your Malus' Law data. You must extract the amplitude of the sinusoid, as well as the theta offset (which represents the relative angle between the incoming polarization axis of the laser light and the vertical analyzer axis).

You must complete both the field calibration analysis and the Malus' Law fit before doing the AC portion of this experiment.

Plot $\Delta\theta$ versus B in Gauss. Find the slope, with uncertainty. The sample is 10.0 cm long. Compute the Verdet constant ν with uncertainty, and compare to the known value $\nu = 0.0013$ degrees/Gauss-cm.