Faraday Rotation

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ABSTRACT

The concept of light polarization has been around since the mid 1800s, discovered by physicists such as Fresnel and Malus. Malus then went on to determine Malus's Law, which states that the intensity of light that passes through a linear polarizer depends on the square of the cosine of the polarizing angle and the maximum intensity. Based on the concepts discovered, Michael Faraday found that an applied magnetic field can influence the polarization of light incident on a transparent medium. This interaction proved that light can be affected by magnetic fields, and similar experiments done by other physicists proved the same for electric fields. Thus, it was determined that light is related to electromagnetic forces. The Faraday effect is experimentally proved by using a solenoid with varying current strengths to find the Verdet constant for a given wavelength of light. Our final Verdet constant values came out to be 17.885 from the DC Volts experiment, 17.71 from the AC Volts Experiment without Lock-in Amplifier, and 21.71 from the AC Volts Experiment with the Lock-in Amplifier. We also got a Cosine Squared wave on the intensity versus polarizer wave proving Malus's Law.

1 Introduction

In the mid 1800s, physicists, such as Fresenl and Malus, experimentally found that certain materials change the polarization of light. In particular, Malus found that the intensity of light that passes through a polarizer depends on the angle and initial intensity. Malus's law is given by

$$I(\theta) = I_{max} \cos^2 \theta \tag{1}$$

where I_{max} is the maximum intensity of the light and $theta$ is the polarization angle.

An easier to use approximation of this law can be derived using the power series expansion and using $\theta = 45$. From this, it is determined that $I_{max} = 2I_0$, where I_0 is the initial intensity. One can also show that the first derivative of $I(\theta)$ also equals $2I_0$. Following this, the approximated Faraday rotation angle is given by

$$\theta = \frac{\Delta I}{2I_0} \tag{2}$$

Based on the concepts of polarization discovered previously, Michael Faraday proposed an idea that that light was related to electromagnetic forces and could be effected by them. After trying to use electric forces to validate his idea, Faraday moved to magnetic fields. He discovered that an external magnetic field effects light propagation inside a medium. He experimentally determined that the polarization plane of light incident on glass rotates when a strong magnetic field is applied along the direction of propagation. This rotation is caused by right and left circularly polarized waves propagating at different speeds due to circular birefringence. These polarizations are still linear, so they can be decomposed into two components with different phases; in turn, this causes a relative phase shift that causes the rotation of the wave's polarization plane. Fig. 1 shows a schematic of this process.

This interaction is now called the Faraday effect or Faraday rotation. This effect confirmed that light and magnetic waves are related, and other similar effects proved that light and electric fields are related.

An easy way to experimentally prove Faraday rotation is with the use of a solenoid that produces a magnetic field. The strength of this field is given by

$$B = \mu NIL \tag{3}$$

where B is the strength of the field, μ is the permeability of free space, N is the number of turns in the solenoid, I is the current strength, and L is the length of the solenoid.

The Faraday effect can be mathematically summed up by

$$\theta = VBl \tag{4}$$

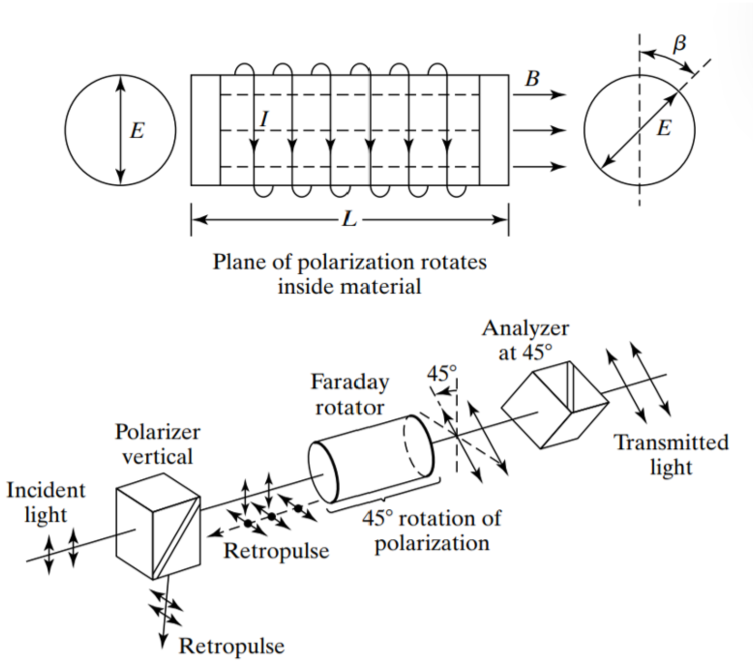

Figure 1. Schematic of the process required to induce Faraday rotation. The upper figure depicts the process with a solenoid and shows that a magnetic field applied along the direction of propagation shifts the electric field by and angle β, also known as the Faraday rotation angle.[1]

where θ is rotation angle measured in radians, B is the magnetic field strength, V is the Verdet constant and l is the length of the material. Using this equation, we can find the Verdet constant by varying the strength of the current applied to a solenoid.

Next, we will go over our experimental setup used to determine this constant, followed by our results and a conclusion.

2 Experimental Setup

Light with wavelength 650nm from the diode laser travels through an initial polarizer whose polarization angle remains constant, a 99.03 mm long rod of SF-57 glass within a solenoid, a second polarizer, and into a photodiode detector. The detector thus measures the transmittance of light through the polarizers and the solenoid. The signal from the detecor is output to either the oscilloscope, the lock-in amplifier, or the voltmeter. Either the DC power supply or the power amplifier supplies current to the solenoid, depending on whether we want the solenoid to produce a steady or oscillating magnetic field. We measure the DC and rms AC current supplied to the solenoid with the ammeter. The toroidal current transformer increases the current by ten times the orginal value, resulting in the voltage of the AC signal directly matching the current supplied to the solenoid. Thus by measuring the AC signal on the scope, we also measure the oscillating AC current supplied to the solenoid. The lock-in amplifier produces the base AC signal, which is then amplified and supplied to the solenoid by the power amplifier. When the detector signal is output to the lock-in amplifier, the lock-in amplifier in turns outputs the DC voltage of only the signal from the detector which is in phase with the base AC signal to the voltmeter.

For all transmittance measurements, we set the second polarizer to the angle which results in half the maximum transmittance. Our solenoid has 1400 total turns and a length of 0.15 m. Based on Eq. 3, the resulting magnetic field strength is $B = 11.1I$ mT/A.

We use the scope and voltmeter to simultaneously measure the current supplied to the solenoid and the voltage of the photodiode detector. We record data for both DC and AC currents between 0 and 3 A. Since the detector voltage indicates transmittance and the solenoid current indicates the strength of the magnetic field, we produce meaningful results by fitting our data to models discussed in the following section.

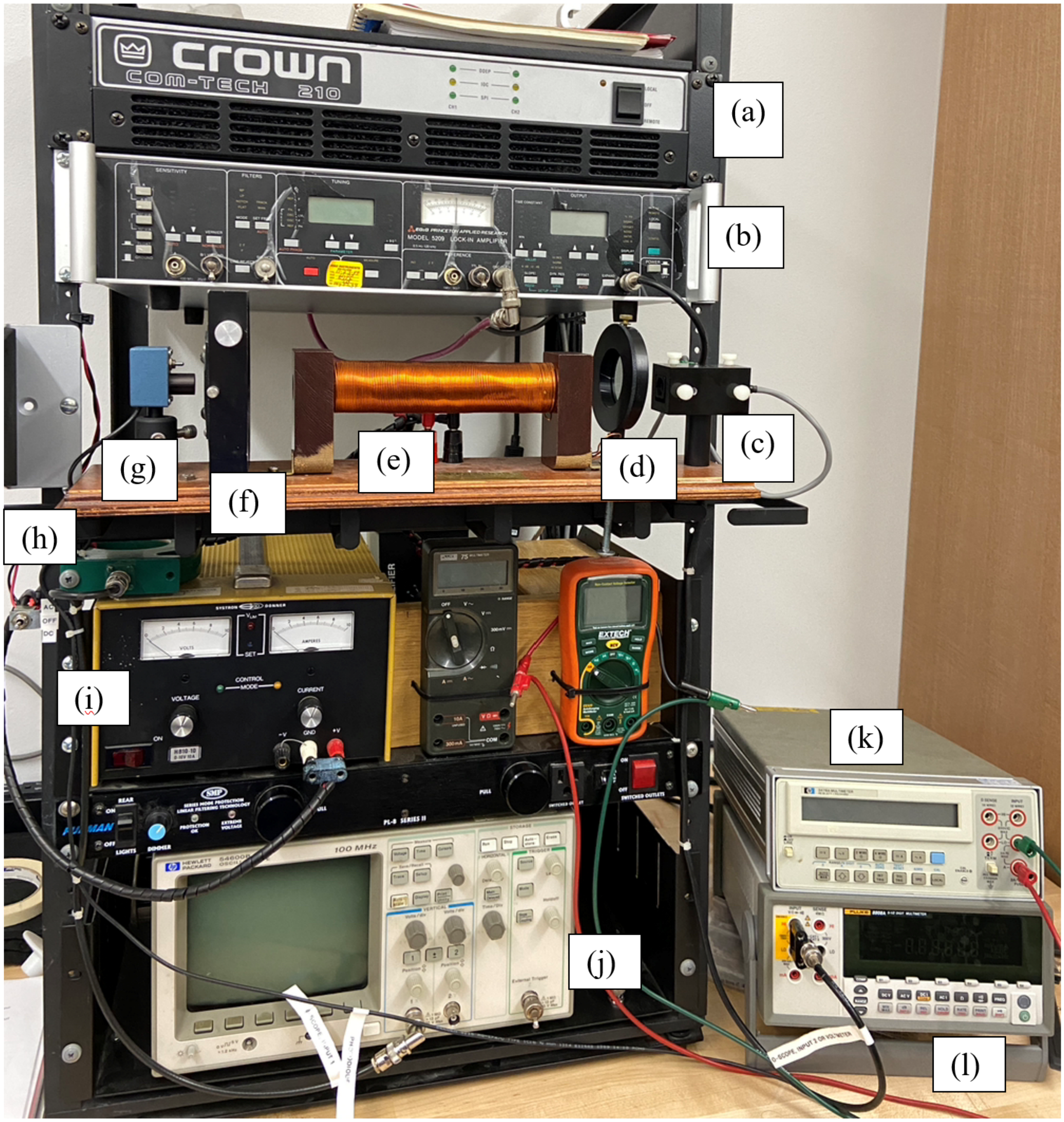

Figure 2. (a) Power amplifier which amplifies the signal from the lock-in amplifier and supplies the signal to the solenoid. (b) Lock-in amplifier which produces our base AC signal for the solenoid and also outputs the DC voltage of the signal from the photodiode detector which is in phase with the base AC signal. (c) Diode laser which emits 650nm light at 30mw. (d) Initial polarizer which remained at constant angle. (e) The solenoid which creates the magnetic field responsible for the Faraday effect. Within the solenoid is a rod of SF-57 glass. (f) The final polarizer for which we found the angle of maximum transmittance. (g) The photodiode detector we used to measure light transmittance through the solenoid and polarizers. (h) Toroidal current transformer which resulted in a 1:1 ratio between the signal peak voltage and the current supplied to the solenoid. (i) Direct current power supply used to create a non-oscillating magnetic field in the solenoid. (j) Oscilloscope used to view the signal for the solenoid current and the voltage signal from the photodiode detector. (k) Ammeter used to measure the current supplied to the solenoid. (l) Voltmeter used to measure the voltage from the photodiode detector.

3 Results

Our first experiment wanted us to prove Malus's Law. As you can see in Fig. 3, the graph follows a cosine squared function as stated by the law. This proves that there is a sinusoidal relationship between intensity and polarizer angle stated by Malus's Law.

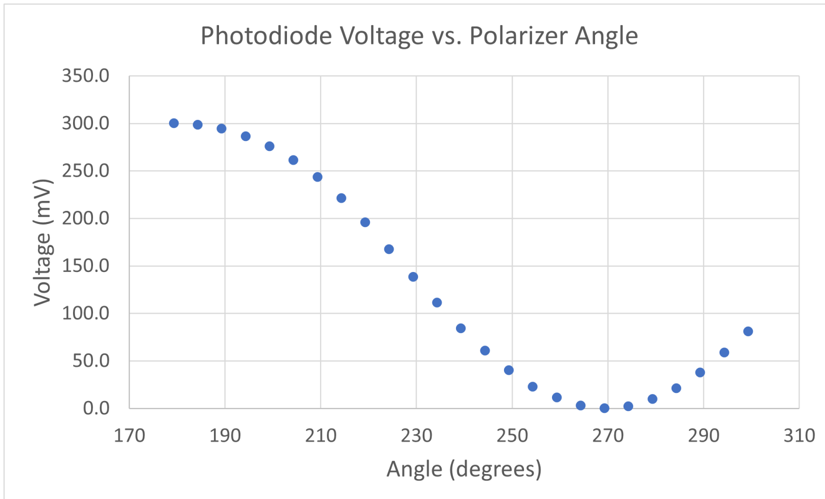

Figure 3. This graph shows the result of plugging into Malus' Law the detector voltage, which is proportional to our laser intensity, vs the theta value, which is the orientation of the polarizer.

We use Eq. 2 to convert our voltage measurements into angles. We then fit our angle and magnetic field strength data to the model of Eq. 4 as in Fig. 4. The slope of our data is the verdet constant for SF-57 glass. We find that from the DC current experiment, our calculated Verdet constant is 17.885. From the AC current experiment without a lock-in amplifier, we determine the Verdet constant to be 17.71. From the AC current experiment with the lock-in amplifier, we determine the Verdet constant to be 21.71.

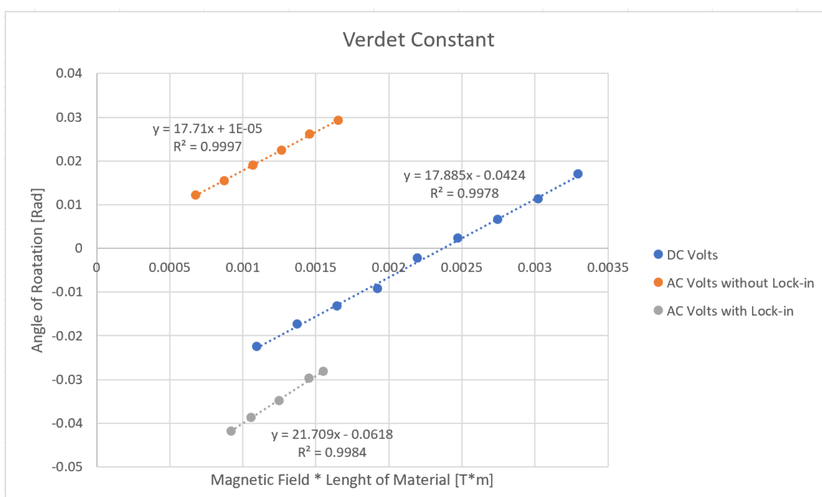

Figure 4. This graph shows 3 different aspects of our experiment. The three graphs are the angle of Faraday Rotation on the y-axis and the magnetic field times the length of the Faraday material (our SF-57 glass) on the x-axis. It shows the obtaining of the Verdet constant of our material through the means of using a DC voltage source, an AC voltage source with no use of a lock-in amplifier, and an AC Voltage source with the use of a lock-in amplifier. The slopes of the lines listed represent the Verdet constant for each method.

4 Conclusions

Our actual estimate for the Verdet constant is 20.3[2]. This means that the result from the DC Experiment has an error of about 11.89%. The result from the AC Volts without a lock-in amplifier has a 12.75% error. And, the result from the AC Volts with the lock-in amplifier has an error of 6.94%. This is expected because the AC Volts with a lock-in amplifier experiment is the most accurate in terms of generating data. Any error we do have can be accounted for by systematic errors such as instrument precision, external light sources present in the room, and rounding errors.

The applications of this experiment include the analysis of mixtures of hydrocarbons because each constituent has a characteristic magnetic rotation. It can yield information about the properties of energy states above the ground level when utilized in spectroscopic studies[1].

References

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