

# Measuring the Verdet Constant in SF-59 Glass

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(Dated: October 27, 2014)

## Abstract

Faraday was the first to experimentally observe that light and magnetic fields were related. The Faraday Rotation is a phase shift in the polarization of light due to propagation through a birefringent material in a magnetic field. We observed Faraday Rotation by calculating the change in polarization angle of red (670nm) light from a polarized laser propagating through SF-59 glass in various magnetic fields. After passing through the material the light went through a polarizing filter. The change in the polarization of the laser light resulted in a change in the relative angle between the laser light and the polarizing filter which changed the intensity measured by the photodiode. The output of the photodiode is a voltage that is proportional to the intensity it measures. We powered the laser with a square wave from a function generator. We then used a lock-in detector to extract only information at the frequency and phase of our signal thus eliminating dc offsets and noise at other frequencies and phases. We determined the Verdet constant which is a material-specific property. The Verdet constant is equal to the proportion between the applied magnetic field, the length of the birefringent material, and the phase shift in the light's polarization angle at a specific wavelength. The Verdet constant determines the angle by which the polarization will change for a given magnetic field strength, wavelength, birefringent material and the length of that material. Using two different experiments, we calculated the Verdet constant of the SF-59 glass rod. In our first experiment we measured the photodiode voltage at various polarization filter angles for four different magnetic fields. Then we plotted voltage versus angle and fitted a curve to the data for each field to find the phase shift between the curves. Using the phase shift we calculated the Verdet constant to be  $19.5 \pm 0.9 \frac{\text{rad}}{\text{Tm}}$ . In the second experiment, we fixed the polarization filter at  $45^\circ$  relative to the light's polarization angle, and measured photodiode voltage for thirteen magnetic fields. As predicted by theory, there was a linear relationship between voltage and field which we used to calculate the Verdet constant. We obtained a second value of  $19.12 \pm 0.05 \frac{\text{rad}}{\text{Tm}}$ . Our values agree with each other within the precision of our measurements and are also in general agreement with the values found by our peers performing similar experiments for the same material.

## I. INTRODUCTION

**Faraday Rotation** refers a phenomenon first observed by Faraday in 1845. It was a landmark discovery, because Faraday theorized and demonstrated the first link between light and magnetism.<sup>2</sup> Faraday discovered that polarized light propagating through certain materials while in a magnetic field experienced a shift in the polarization angle. This effect occurs in materials which have different refractive indices for left circularly polarized (LCP) light and right circularly polarized (RCP) light when they are in a magnetic field. These materials are called birefringent. Polarized light can be written as the vector sum of LCP and RCP components; when it propagates through a birefringent material, therefore, its components experience different phase shifts leading to a total phase shift in the light's polarization.<sup>1</sup> The magnitude of the phase shift depends on three factors: the strength of the magnetic field, the distance that the light travels in the material and the properties of the material itself. The phase shift which will result from propagation through a specific material, for a given magnetic field and length of material, is given by the Verdet constant ( $v_c$ ) which has units of  $\frac{\text{radians}}{\text{tesla meter}}$ . Thus the equation for total phase shift is  $\Delta\theta = v_c BL$ .

In this paper, we measure the Verdet constant of SF-59 glass using the expected linear relationship between phase shift and magnetic field. We also describe a second experiment which we performed to confirm the value we obtained in our first experiment. **Comments on Introduction:** very clear, except you haven't defined the variables used in your equation for phase shift. One way to do this is to follow your equation with the phrase "where  $v_c$  is the Verdet constant,  $B$  is the .... etc." Another is to insert the symbol where you first mention it in words, such as "The magnitude of the phase shift depends on three factors: the strength of the magnetic field  $B$ , the distance ...."

## II. METHODS

Our experimental setup was based off the TeachSpin teaching manual.<sup>2</sup> We used a TeachSpin FRI-A apparatus consisting of a diode laser, a solenoid, a polarizing filter and photodiode. To observe Faraday Rotation and measure the Verdet constant we used a SF-59 glass rod. SF-59 glass is heavy flint glass with a high lead content. The manufacturers dope silicone glass with lead because the high lead content increases the Verdet constant

of the glass, making it easier to observe Faraday Rotation.<sup>3</sup> We placed the glass rod in the center of the solenoid. The length of our rod was 5 cm shorter than the solenoid so that the magnetic field was approximately constant across the length of the rod and we could neglect the severe drop in magnetic field near the edges of the solenoid.

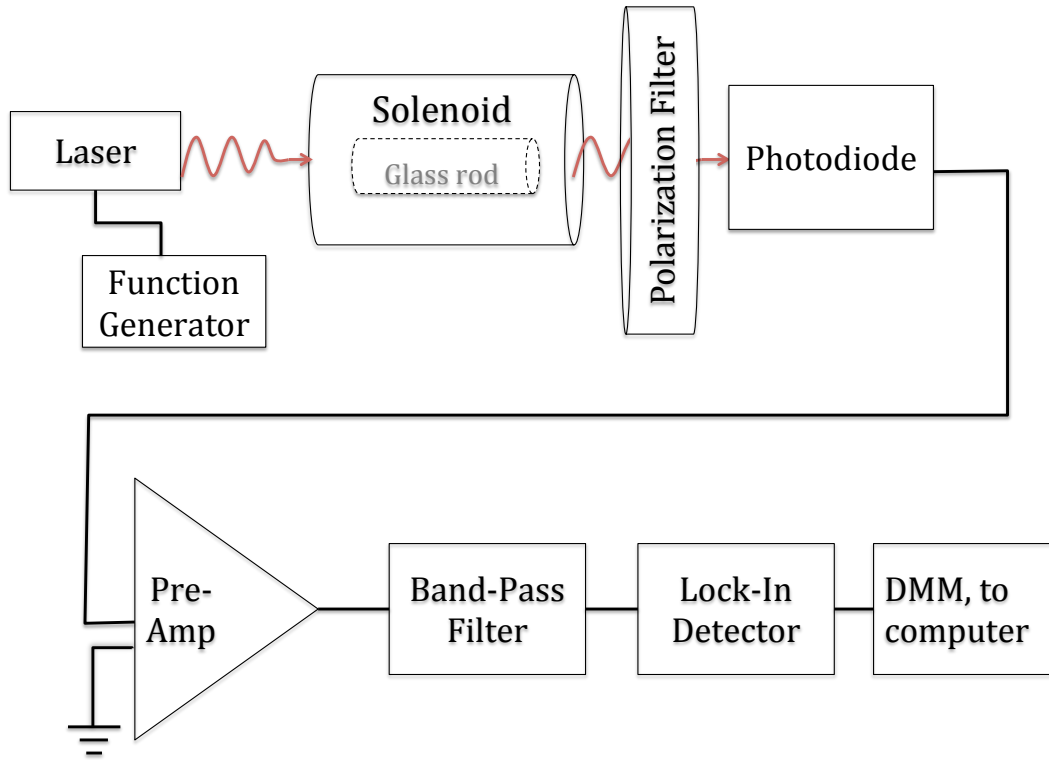


FIG. 1. The set-up of our experiment. The light source was a laser, powered by a function generator. We sent the beam through a solenoid containing the glass rod and then through a polarization filter. A photodiode at the other end measured the light intensity and outputted a voltage. This signal went through a pre-amp, bandpass and lock-in detector to remove offsets due to ambient light and photodiode drift. The much clearer signal was then measured with a multimeter connected to a computer.

Our power source to the solenoid was a Keithley 2230-30-1 Triple Channel DC Power Supply which we used on current control throughout our experiments. We connected the two **3 volt** terminals in parallel so that we could obtain a maximum current of 3 amps through the solenoid. **3 V or 30 V?** By varying the current through the solenoid we could

change the magnetic field through the glass rod. We measured the magnetic field using a TEL-Atomic Inc. Smart Magnetic Sensor for a current of 2A and obtained a field of 21.8mT at the center of solenoid decreasing to 20.5mT at the edges of the glass rod. We took the average of this range to be our best value and difference between high and low values divided by two to be our uncertainty. To obtain field values for other currents we exploited the linear relationship between magnetic field and current.

better than that simple average would be weighted average such as  $\frac{1}{N} \sum_{x_1=-L/2}^{x_N=L/2} B(x_i)$  for equally spaced data measurements or  $\frac{1}{L} \int_{-L/2}^{L/2} B(x)dx$  (if you first fit your data to a smooth function for B(x)). The difference between your simple average and these would be particularly important when measuring a liquid sample that extends outside the solenoid better than that simple average would be weighted average such as  $\frac{1}{N} \sum_{x_1=-L/2}^{x_N=L/2} B(x_i)$  for equally spaced data measurements or  $\frac{1}{L} \int_{-L/2}^{L/2} B(x)dx$  (if you first fit your data to a smooth function for B(x)). The difference between your simple average and these would be particularly important when measuring a liquid sample that extends outside the solenoid

We used a 670 nm diode laser powered by a Rigol DG1022A function generator. From the function generator we obtained a 0 to 4 V square wave which turned the laser on and off at frequency of 400Hz. After passing through the solenoid, the polarized light from a 4 volt 670 nm laser diode passed through a second polarizer before being measured by a photodiode. Is the photodiode measuring the polarization or the light intensity? Be specific The output of the photodiode was a voltage proportional to xxx? that contained significant noise and offsets due to changes in the intensity of the ambient light of the room and the drift of the photodiode is this drift due to something other than changes in ambient light? explain. To remove the noise and offsets, the 4 volt 670 nm laser diode polarized light source was square-wave modulated at a frequency of 400 Hz and the resulting measured signal from the photodiode was run through a preamp, a bandpass filter and a lock-in detector. The preamp was with respect to ground. What does this mean? That you were using the pre-amp in single-ended A - ground instead of differential A - B mode? The bandpass filter removed frequencies both higher and lower than our signal and ensured that we had only the first harmonic. Finally, we used lock-in detector to select the specific frequency and phase of our signal. The final signal had very little noise can you be more specific by any chance? percent uncertainty? some other measure? and was stable even when the room lights were turned off and on.

The paragraph above needs an introductory transition sentence. Why are we suddenly talking about how the laser is powered? You might consider making your third sentence your first. Also, might be clearer to first describe dc detection.

The final signal from the lock-in detector was then measured with a Keithley 2100 DMM. To facilitate data collection we used a computer program (helpfully provided by our instructors) called "Keithley DC Incremental Write." . The program would record a specified number of values for voltage then average them to obtain a single data point. Therefore, our results for each point were the mean of the measured points at that intensity with an uncertainty given as the standard deviation of the mean.

use ‘ ‘ and ’ ’ to put a word or sentence in quotes.

Example: "quotation" has the word quotation in quotes.

For our **fist** experiment, which we called the changing theta experiment, we measured the photodiode voltage (which is proportional to light intensity) **while rotating the polarizing filter**. We started with no current through the solenoid and an angle of  $90^\circ$  between the polarized laser and the polarizing filter. The difference in angle between the polarization of the laser and the polarization of the filter is referred to as the relative angle throughout this paper. We found where the relative angle was  $90^\circ$  by observing where our intensity and measured voltage were at a minimum. We then measured the voltage every  $10^\circ$  for a single rotation ( $360^\circ$ ). For this experiment we set the computer program to average over 16 values for each data point. We repeated this measurement for currents of  $I = 1\text{A}$ ,  $I = 2\text{A}$  and  $I = 3\text{A}$ .

You haven't defined theta at this point. You either need to introduce the  $V = A \cos^2(\theta + \theta_0)$  equation earlier or give it a different name, such as 'changing polarizer angle' experiment or 'fixed field' experiment.

Also, instead of **while rotating the polarizing filter** consider **as a function of polarizer angle, while holding the magnetic field steady**.

For our second (changing field) experiment, we set our relative angle to  $45^\circ$ . We chose this angle because at  $45^\circ$  the slope of the intensity versus angle is steepest. This means that a change in polarization angle leads to the largest change in intensity when the relative angle is  $45^\circ$ . We then measured the photodiode voltage for currents  $0\text{A}$ ,  $\pm 0.5\text{A}$ ,  $\pm 1\text{A}$ ,  $\pm 1.5\text{A}$ ,  $\pm 2\text{A}$ ,  $\pm 2.5\text{A}$  and  $\pm 3\text{A}$ . For each change in current the initial voltage reading would drift

as the solenoid heated and resistance changed. We allowed the voltage to stabilize before starting data collection. For this experiment we set the computer program to average over 100 values for each data point.

### III. RESULTS

From the changing theta experiment, we got 36 data points for each current, i.e. 0A, 1A, 2A, and 3A, shown in Figure 2. The red points are the measurements taken without a magnetic field, the blue points were taken with 1A of current passing through the solenoid, the green points with the current at 2A, and the orange points at 3A. The curve fits are the function  $V = A \cos^2(\theta + C)$ , with  $A$  held constant at 6.2845 V (obtained from the first curve fit), and  $C$  calculated by the curve fit. We are interested in the change in  $C$  between curve fits because this gives us the change in the relative angle caused by applying a range of magnetic fields. The uncertainty in relative angle is due to difficulty reading the increments on the polarizing filter. The uncertainty in photodiode voltage is the standard deviation of the mean and is too small to be seen in Figure 2.

From the measurements at a 45° relative angle while changing magnetic field, we obtained the results shown in Table I. Uncertainty in voltage is again the standard deviation of the mean.

The error voltage values in Table 1 seem unbelievable. Do you really have 1 part in 10<sup>9</sup> precision?

### IV. ANALYSIS

#### A. Changing Theta Experiment

We analyzed the data from both experiments separately to calculate two values for the Verdet Constant. For the changing theta experiment, we used IgorPro to fit the function  $V = A \cos^2(\theta + C)$  to the data in Figure 2. We then calculated the magnetic field from the applied current and our measurements of magnetic field for a current of 2A. The phase shift values are the difference between the C-values of the curve fits. The results are in Table II. The uncertainty in the BL was calculated from the estimates of error in our magnetic field measurements and length measurements for the glass rod. Uncertainty came primarily

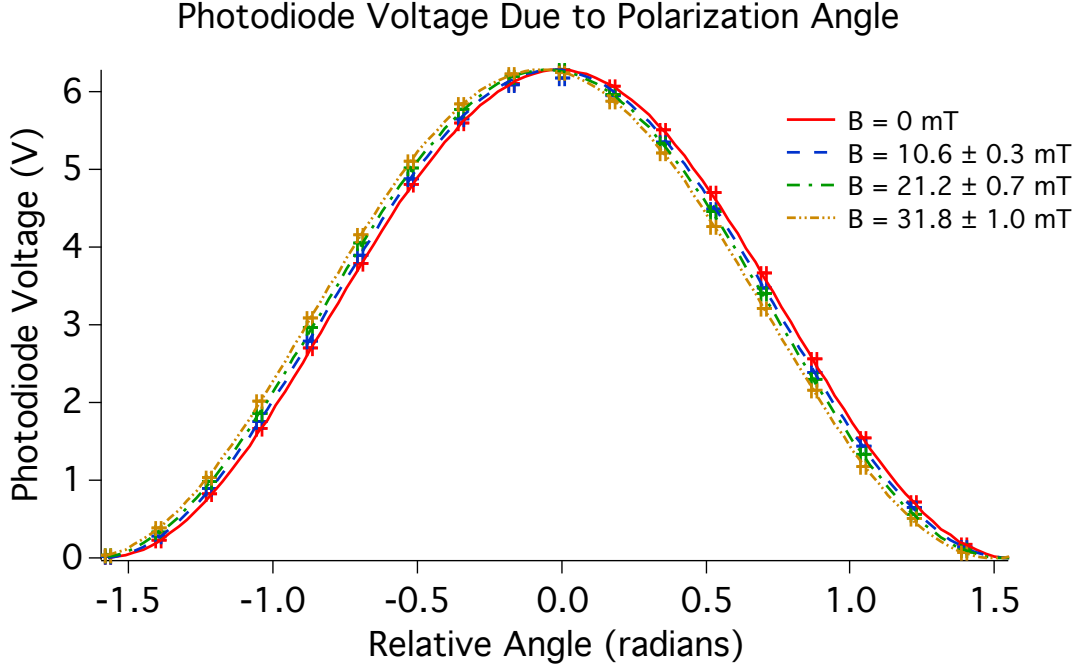


FIG. 2. Photodiode voltage (proportional to light intensity) plotted against relative angle from  $-\frac{\pi}{2}$  to  $\frac{\pi}{2}$  radians. The red points are the measurements taken without a current in the solenoid, the blue points were taken with 1A of current, the green points with the current at 2A, and the orange points at 3A. The curve fits are the function  $V = A \cos^2(\theta + C)$ . Faraday Rotation explains the phase shifts between the data sets at different magnetic fields values.

from lack of precision on the part of the magnetic field sensor and inaccuracy in determining the sensor's position within the closed solenoid. There was some uncertainty in the length measurement, but it was a much smaller percentage of our best value than the percentage uncertainty in magnetic field.

We then plotted the phase shifts versus the magnetic field multiplied by the length of our rod, which gave us Figure 3. From the theory we know that  $\Delta\theta = v_c BL$  therefore we would expect our data to be linear and the Verdet constant to be the slope. A linear fit matches our data well, passing through every point within uncertainty. From the slope of the linear fit we obtained a value for the Verdet constant of  $19.5 \pm 0.9 \frac{\text{rad}}{\text{Tm}}$ .



TABLE I. Voltage readings from the photodiode for various currents through the solenoid or the changing field experiment, with the magnetic fields produced by those currents for a fixed relative polarizer angle of  $45^\circ$ .

Current (A)	Field (mT)	Error Field (mT)	Voltage (V)	Error Voltage (V)
-3	-31.8	-1	2.822	1.30E-10
-2.5	-26.5	-0.9	2.887	5.47E-10
-2	-21.2	-0.7	2.951	3.72E-10
-1.5	-15.9	-0.5	3.016	3.78E-11
-1	-10.6	-0.3	3.082	8.98E-10
-0.5	-5.3	-0.15	3.145	9.03E-10
0	0	0	3.211	1.18E-09
0.5	5.3	0.15	3.272	1.16E-10
1	10.6	0.3	3.338	2.05E-09
1.5	15.9	0.5	3.404	2.13E-09
2	21.2	0.7	3.468	6.96E-10
2.5	26.5	0.9	3.534	1.12E-09
3	31.8	1	3.599	1.05E-09

TABLE II. Curve fit data and calculated phase shifts for changing angle experiment, with magnetic fields calculated from the applied currents.

I (A)	BL (mT cm)	$\delta$ BL (mT cm)	C (rad)	$\delta$ C (rad)	$\Delta\theta$ (rad)	$\delta\Delta\theta$ (rad)
0	0	0	0.0088553	0.001	0	0.002
1	108	4	0.030849	0.0014	0.022	0.0024
2	215	8	0.049599	0.0013	0.0407	0.0023
3	323	12	0.072754	0.0015	0.0639	0.0025

## B. Changing Field Experiment

To get the Verdet constant from our changing field experiment, we first calculated the values of magnetic field times length for currents from -3A to 3A in steps of 0.5As, see

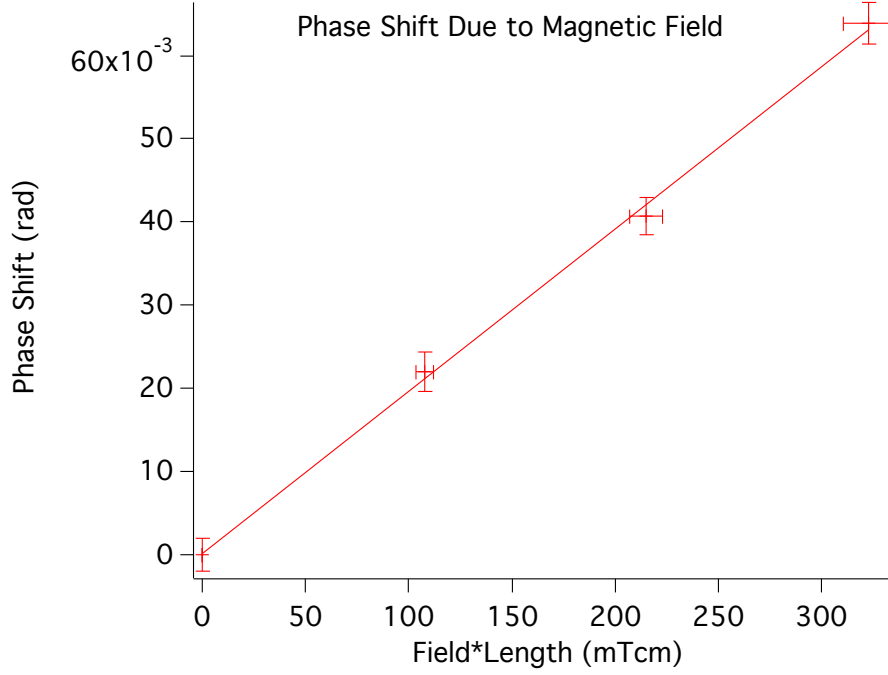


FIG. 3. A plot of Table II, applied magnetic field (times length of the birefringent material) versus the resulting phase shift in the polarization of the light. The slope of a linear fit of this plot gives a value for the Verdet constant of the glass rod.

Figure I. As before we calculated the field from our measured field for 2A and the linear relationship between field and current. We multiplied the magnetic field by the length of our glass rod ( $L = 10.15$  cm) to get values for  $BL$ .

We then plotted the results of Table I in Figure 4. From the slope of the linear fit we got  $\frac{\delta V}{\delta BL} = 0.0012018 \pm 1.8 \times 10^{-6} \frac{V}{mT \text{ cm}}$

Since, as shown above,  $v_c = \frac{d\theta}{dBL}$ , we can use the chain rule for derivatives and get:

$$\frac{dV}{dBL} = \frac{dV}{d\theta} \frac{d\theta}{dBL} = \frac{dV}{d\theta} v_c \quad (1)$$

Therefore

$$v_c = \frac{\frac{dV}{dBL}}{\frac{dV}{d\theta}} \quad (2)$$

From Figure 4 we got  $\frac{dV}{dBL} = 0.0012018 \pm 1.8 \times 10^{-6}$ . To get  $\frac{dV}{d\theta}$ , we took the derivative of the function  $V = A \cos^2(\theta)$  at  $\theta = \pi/4$  and obtained  $\frac{dV}{d\theta} = -A$ , and from the fit to the zero field data in Figure 2,  $A = 6.285 \pm 0.008 \frac{V}{mT \text{ cm}}$ .

Dividing these two results, we get  $v_c = \frac{dV}{dBL} \div \frac{dV}{d\theta} = 19.12 \pm 0.05 \frac{rad}{Tm}$ . This result agrees with the value we obtained from the changing theta experiment within uncertainty.

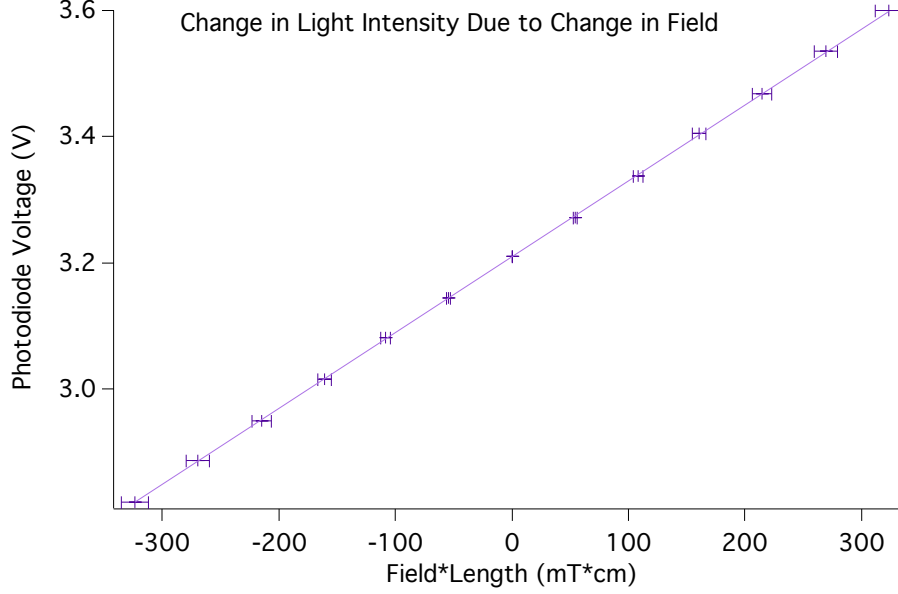


FIG. 4. A plot of Table I, the applied magnetic field (times the length of the refracting material) versus the voltage measured by the photodiode for that field. The slope of a linear curve fit to this plot can be used to calculate the Verdet constant of the material.

## V. DISCUSSION

All of our experimental results are consistent with theoretical expectations. In Figure 2 the intensity of the light, given by voltage from the photodiode, showed a  $\cos^2 \theta$  relationship with the relative angle between as was expected. For the changing theta experiment the relationship between phase shift and magnetic field had a constant, positive slope, Figure 3, which is reassuring since slope should be the Verdet constant, a constant positive value. For the changing field experiment we expect intensity to depend linearly on field because a change in field causes a proportional change in phase shift and the relationship between intensity, i.e. voltage, and phase shift to be linear for small changes in phase. The values that we obtained for the Verdet constant from both experiments agreed with each other within uncertainty. Further they are within the range of values obtained by our peers performing similar experiments.

The biggest sources of error in our experiments came from our measurement of the magnetic field and the imprecision of our angle measurement on the polarizing filter. To decrease error in future experiments we would suggest using a more accurate magnetic field sensor,

and to measure the magnetic field for all currents used in the experiment. A more precise profile of magnetic field through the solenoid would also allow for integration of the field along the length of the material. This would give less uncertainty in  $B$  than the constant field approximation that we used. Finally, a polarizing filter that showed smaller increments for angle would help lower the uncertainty in relative angle.

## VI. CONCLUSION

Both of our experiments allowed us to calculate values for the Verdet constant. But that does not mean that both methods are equally good. The changing theta experiment relies on there being enough of a phase shift in the data points for the various magnetic fields to have a larger than uncertainty difference in the phase of the curve fits. In our experiment we did have significant phase shifts between data sets because we were working with a material specifically manufactured to increase the magnitude of the faraday rotation. However, this method would not be a good choice to use for a material with a smaller Faraday Rotation. Additionally, as the larger uncertainty suggests, this method is not as precise as the changing field experiment.

The changing field experiment has its own drawbacks. To calculate the Verdet constant we assumed that the relative polarization angle was  $45^\circ$ . If the actual relative angle diverted from  $45^\circ$  than the changing field method would not be accurate. However the ability to measure the Verdet constant for materials with smaller faraday rotations might be an acceptable trade off for the loss in accuracy.

Both methods could be modified to measure the Verdet constant for different wavelengths. Repeating the measurement taken at various magnetic field for an entirely different wavelength would allow the difference in the Verdet constant to be calculated for various wavelengths.

Calculating the Verdet constant and being able to quantify Faraday Rotation has a number of applications including in astronomy, optics and chemistry. Faraday Rotation is used to map the magnitude of magnetic fields in space and to build optical 'switches' that allow light to pass through in one direction but severely attenuate it when it moves in the other direction. Even without the modern applications, Faraday Rotation will always be significant as the first experimental evidence of a connection between magnetism and light which

paved the way for our understanding of electromagnetism.

This would be a good place to discuss the relative merits of the two measurement methods, which one is likely to have better accuracy, which one is likely to have better precision (remember the difference?), and which you would use for a follow on measurement of a material with a much smaller Verdet constant, for example. This would also be a good place to discuss how you might modify the experiment to measure the wavelength dependence, as well as to mention important technological applications of this effect (for example in chemistry and/or fiber optic telecommunications).

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<sup>1</sup> Adrian C. Melissanos and Jim Napolitano, *Experiments in Modern Physics* 2nd edition (Academic Press, Boston, 2003)

<sup>2</sup> Jonathan F. Reichert, *Faraday Rotation: Instructor's Guide to TeachSpin's FRI-A Apparatus*

<sup>3</sup> Hans Bach and Norbert Neuroth, *The Properties of Optical Glass* 2nd edition (Springer Science and Business Media, Mainz, Germany, 1998)