The Faraday Effect

Jason D. Darfus
Physics Department, The College of Wooster, Wooster, Ohio 44691
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An optically transparent piece of "glass" is placed between two large electromagnets and subjected to varying magnetic fields by changing the amount of current running through the magnets. This has an effect on the object placed in the magnetic field such that polarized light passing through the object will become rotated by some amount. This effect is called the Faraday Effect and can quantitatively be described by the angle through which the light is rotated, the magnetic field, and the thickness of the optical piece. A proportionality constant inherent to the piece is known as the Verdet constant and is the angle per unit length per unit magnetic field. In this experiment, I measured the Verdet constant to be $(1.22 \pm 0.11)x10^{-2} \frac{\min}{Gauss \cdot cm}$ in comparison to the published value of $0.016 \frac{\min}{Gauss \cdot cm}$. (Hodgman, Handbook of Chemistry and Physics, vol.2, 1953).

INTRODUCTION

Faraday Rotation: A plane-polarized wave can be decomposed into two circularly polarized waves. The rotation of the plane of polarization of light as it propagates through the optical piece in a direction parallel to an applied magnetic field is called the Faraday effect, or Faraday rotation. The amount of rotation is usually given by the empirical law $\theta = VBl$, where θ is the angle of rotation, V is the Verdet coefficient, B is the magnetic field value, and l is the thickness.[1]

A modern picture of Faraday rotation emerges from the quantum-mechanical response of an atom to a magnetic field. In this picture the atomic absorption and dispersion are both affected by the field, and in this sense the Faraday effect is to dispersion what the Zeeman effect is to absorption (or emission).[2]

THEORY

The rotation due to a magnetic field may be expressed in terms of e/m, the ratio of the charge of an electron to its mass. According to the theory of Lorentz, an electron moving in its orbit about an atomic nucleus will change its frequency of revolution which in turn leads to a rotation of the plane of polarized light through the affected object. This angle of rotation θ has been shown to be

$$\theta = \frac{e}{2mc^2}\lambda B \frac{dn}{d\lambda} = VBl \qquad \textbf{(Eq. 1)}$$

where e is the charge of an electron in e.s.u, m is the mass of the electron in grams, c is the speed of light in cm/sec, λ is the wavelength of light, B is the magnetic field strength in oersteds, $\frac{dn}{d\lambda}$ is the derivative of the index of refraction with respec to the wavelength, and V is the Verdet constant. The amount of rotation was found to be proportional to the strength of the magnetic field and the distance the light must pass through the medium.[3]

EXPERIMENT

The experiment is set up so that a Kepco DC power supply sends a current to two water-cooled Cenco electromagnets with tapered poles. An optical piece (transparent solid medium) is placed between the poles of the magnets. The magnets are designed in such a way that a light beam can be sent though the apparatus from one side to the other. A Melles Griot helium neon laser (1mW max) is sent first through an Oriel beam polarizer then through the magnet setup as well as the optical piece. After emerging from the magnetic field, the beam is sent though an Oriel polarized beam analyzer with micrometer adjuster. From here, the beam is perpendicularly centered onto a cosine diffuser photo diode, which is attached to a linear/log optometer from United Detector Technology. Magnetic field strengths are measured using a gauss meter with probe from Applied Magnets Laboratory.

To start with, it was necessary to calibrate the magnetic field as a function of current. It is observed that the ratio of the average magnetic field $\overline{B}$ measured at various points between the poles versus the minimum magnetic field strength B_{min} as measured in the center of the space between the poles is a constant:

$$\frac{\overline{B}}{B_{min}} = 1.110 \pm 0.002 \qquad \textbf{(Eq. 2)}$$

independent of the value of the current being applied.

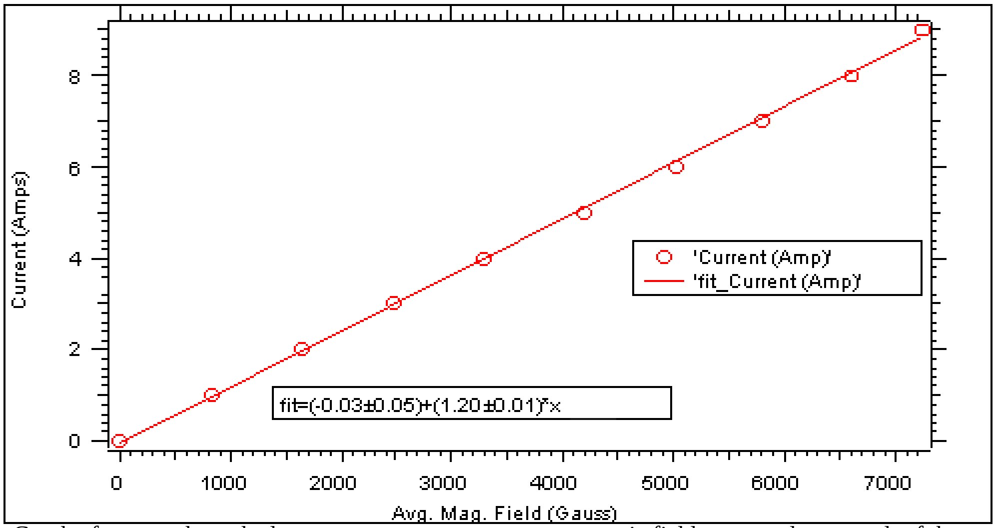

Figure 1. Graph of current through electromagnets versus average magnetic field generated as a result of the current flow.

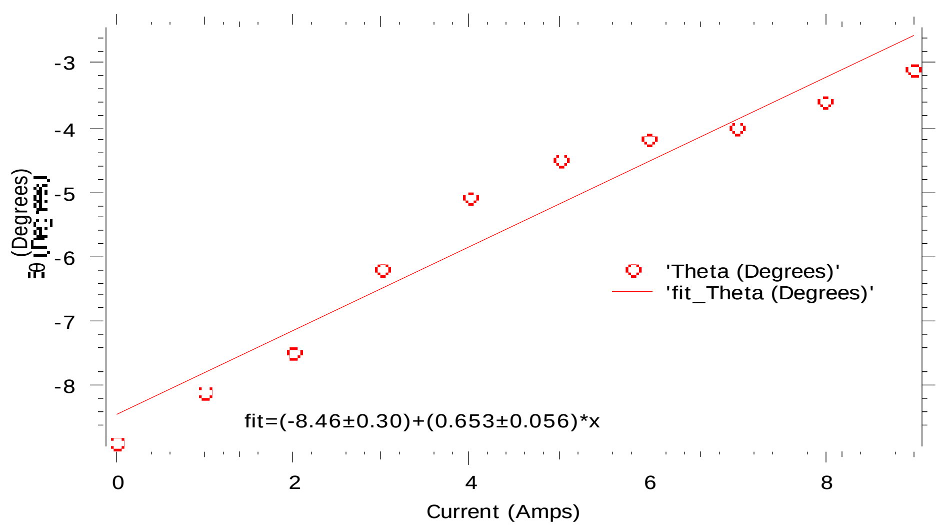

Figure 2. Graph of angle of rotation of polarized light due to Faraday Rotation as a function of current to the electromagnets.

In order to see how much the polarized beam is rotated as a function of the magnetic field strength, we needed to find out how the current through the magnets affects the average magnetic field strength $\overline{B}$. Figure 1 shows this relationship.

Next, we need to find out how the rotation of the polarized light is affected as a function of the current through the magnet coils. In increments of 1A, the rotation of the light is recorded by reading this from the micrometer on the polarized light analyzer. These values are plotted in a graph of angle vs. current (Figure 2) and the product of the slopes of Figures 1 & 2 gives the answer to Eq. 4.

The purpose of the beam polarizer and analyzer combination is so that the amount of rotation of the polarized beam as a result of the magnetic field's effect on the optical piece can be measured. By consistently measuring minimal light intensity for each amount of current through the magnets, we can read the change in rotation from the polarized beam analyzer/micrometer. This can then be converted to a corresponding angle using a conversion sheet provided by the Oriel manufacturing company.

Current to magnet (Amps)	Micrometer (cm)	Angle (Degrees)
0	11.68±0.5	-8.9±0.8
1	11.12±0.5	-8.1±0.8
2	10.76±0.5	-7.5±0.8
3	9.95±0.5	-6.2±0.8
4	9.24±0.5	-5.1±0.8
5	8.84±0.5	-4.5±0.8
6	8.70±0.5	-4.2±0.8
7	8.57±0.5	-4.0±0.8
8	8.29±0.5	-3.6±0.8
9	7.98±0.5	-3.1±0.8

Table 1. Micrometer readings from polarizer analyzer for minimal light transmission depending on what current was passed through the magnets' coils.

The rotation of the circularly polarized light wave due to the Faraday Effect is given by Eq. 1. In the case of this experiment, we are looking for the Verdet constant of an optical piece of some kind. Once this is known, we can determine what kind of material the piece is made of. In order to determine what the Verdet constant is, the above equation that is used to find the angle of Faraday rotation can be re-written as

$$V = \frac{1}{l}\frac{d\theta}{d\overline{B}} \qquad \textbf{(Eq. 3)}$$

where, in this case, we are looking at the change in angle per change in magnetic field. The magnetic field here is taken as the average magnetic field over the open space in between the electromagnets in which the optical piece is placed. Since we already know that the total angle of rotation is a function of current or magnet field strength, it would make the job of solving the above equation easier if the derivative were to be broken down such that

$$\frac{d\theta}{d\overline{B}} = \frac{d\theta}{dI}\frac{dI}{d\overline{B}} \qquad \textbf{(Eq. 4)}$$

This way, two graphs, one of angle vs. current and current vs. magnetic field strength, can be plotted in which the product of the two slopes will equal the change in angle per change in magnetic field. This is what was done, and graphs are shown as Figures 1 & 2.

ANALYSIS & INTERPRETATION

Once the variables involved have been measured, and knowing the length of the path light has to travel through the optical medium (3.85 ± 0.03 cm), it is a simple matter to solve for the Verdet constant:

$$V = \frac{1}{l}\frac{d\theta}{d\overline{B}} = \frac{1}{(3.85 \pm 0.03)cm}(0.653 \pm 0.056\ {}^{\circ}\!/_{amp})$$

$$x(1.2 \pm 0.01)x10^{-3}\ {}^{amp}\!/_{Gauss}$$

$$V = 2.04x10^{-4}\ \frac{\text{deg}}{Gauss \cdot cm}$$

$$V = (1.22 \pm 0.11)x10^{-2}\ \frac{\text{min}}{Gauss \cdot cm}$$

My experimental value for the Verdet constant is 17% out of agreement (including max. uncertainty) in comparison to various published values for solid materials. Table 2 lists various solid substances and their Verdet constants.

Substance	Verdet Constant (min/Gauss cm)
Glass, Jena (barrium crown)	0.022
(phosphate crown)	0.016
(light flint)	0.032
(heavy flint)	0.061
(very heavy flint)	0.089

Table 2. Table of Verdet constants for various glass-like substances. [Ref.4]

CONCLUSION

The focus of this experiment was to explore the effects of Faraday Rotation on an optically transparent object and to find the object's Verdet constant which is the constant term in equating the angle of rotation to the magnetic field and thickness of the piece being studied. In this experiment, I didn't have the luxury of knowing beforehand what object I was studying. I had to first find some quantity that would help me identify the piece. Since the focus of the experiment was to find the Verdet constant, that may as well be the value I look for. Another possibility would have been to find the index of refraction and identify the piece that way.

After measuring a Verdet constant of $(1.22 \pm 0.11)x10^{-2}\ \frac{\text{min}}{Gauss \cdot cm}$, I compared this value to different published values and found it most closely resembles that of phosphate crown glass. Luckily, this is the name by which other students who performed this experiment before me had referred to the same experimental object.

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[1] Michael Bass, Handbook of Optics 2nd edition, vol.2 (McGraw-Hill, Inc., 1995), p.36-45.

[2] D.A. Van Baak, Am. J. Phys. **64** (1996).

[3] J.J. Lamor, Aether and Matter, (Cambridge University Press, 1900), p.352.

[4] Charles D. Hodgman, M.S., Handbook of Chemistry and Physics 35th ed., vol.2, (Chemical Rubber Publishing Co., 1953), p.2737.