The Faraday Effect

Erica N. Bramley
Physics Department, The College of Wooster, Wooster, Ohio 44691
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A magnetic field is applied parallel to a laser beam which passes through a glass medium. The angle of polarization of the light rotates as a result of changing the magnetic field. The angle of polarization is equal to a constant times the magnetic field strength and the width of the medium transversed. That constant is the Verdet constant. The measured value for the Verdet constant of phosphate crown glass is $(18.6 \pm 1.8) \times 10^{-3}$ min/(cm*gauss). The standard value for the Verdet constant for phosphate crown glass is (16.1×10^{-3}) min/(cm*gauss). (Hodgman, Handbook of Chemistry and Physics, 1949).

INTRODUCTION

By observation of the Faraday effect, the Verdet constant for solids, liquids and gas can be determined. In 1845 Michael Faraday discovered that a block of glass becomes optically active when subjected to a strong magnetic field. After continued observation it was realized that the amount of rotation of plane polarized light for all substances is proportional to the magnetic field strength and the distance traveled by the light. Each substance has a constant associated with it known as the Verdet constant. This was shown experimentally. A complete theory was not presented until P. Zeeman, in 1896, observed a similar effect with a sodium flame and the splitting of spectral lines. Lorentz was the first to finally present a theory to explain the phenomena using electron theory of matter. The Faraday effect observes changes in rotation of plane polarized light sent through a solid, liquid or gas that is due to a magnetic field. In this experiment phosphate crown glass is subjected to a varying strength of magnetic field while a HeNe laser with a light path parallel to the magnetic field is sent through the glass.

THEORY

The rotation of the polarized light in the Faraday effect can be expressed using terms of the ratio of the charge of an electron to its mass.[1] According to the theory of Lorentz, based on electron theory of matter, an electron moving in its orbit about an atomic nucleus will change in frequency once in an external magnetic field and cause the plane of polarization of light to rotate by an angle θ :

$$\frac{\theta}{l} = \frac{e}{2mc^2} \lambda B \frac{dn}{d\lambda} = VB \qquad (1)$$

where $\frac{\theta}{l}$ is radians per centimeter of medium traversed, e is the charge on the electron (e.s.u), m is the mass of the electron (grams), λ is the wavelength of light, B is the magnetic field (oersteds), $\frac{dn}{d\lambda}$ is the derivative of the index of refraction with respect to wavelength and V is the Verdet constant. The amount of rotation of the polarized light was found experimentally to be proportional to the magnetic field strength and the distance the light travels through the substance. As shown in equation 1. Equation 1 can be rewritten as the change in rotation of the plane of polarization caused by a change in the magnetic field strength so that the Verdet constant is equal to:

$$V = \frac{\Delta\theta}{\Delta B l} = \frac{e\lambda}{2mc^2} \frac{dn}{d\lambda} \qquad (2)$$

For glass that is in the visible spectrum the Verdet constant decreases as wavelength increases. This is due to the fact that the derivative of the index of refraction with respect to the wavelength decreases as the wavelength increases.[1]

EXPERIMENT

The medium transversed is a cube of phosphate crowned glass made of two right angle prisms. A Cenco water cooled electromagnet with tapered pole pieces is driven by an adjustable DC power supply (Kepco #ATE 100-10M) and is used to create the magnetic field. The magnetic field is measured by a gauss meter and probe from Applied Magnets Laboratory. An Oriel polarizer and analyzer with a micrometer adjuster is used to polarize the HeNe Melles Griot (1mW max) laser beam and monitor the angle of polarization. The photo diode (Cosine Diffuser) receives the out coming laser beam and the Linear/Log Optometer

(United Detector Technology # 350) translates the light intensity into usable values. Place the HeNe laser at one end of the electromagnets . Line up the laser beam so that it goes directly through the center of each pole. Place a polarizer between the laser and the magnets. Place a beam analyzer with a micrometer gage on the opposite side of the electromagnets. Once a change in plane of polarization of the light is detected, the angle change can be measured.

The current of the power supply for the electromagnets can reach 9 Amps. At each current adjust the polarizer so that the photo diode reads the lowest intensity. The micrometer and the current on the power source are recorded. The amperage is changed in steps of 0.5 Amps.

The gauss meter is calibrated. The magnetic field lines between the poles are plotted at 8 and 3 Amps using the gauss meter. Starting at 9 Amps and ramping down to 0, the magnetic field is measured at the center of the poles.

To calculate the change in angle of the analyzer from the micrometer reading a plot is made of calibration data provided by Oriel. The plot is in Figure 1.

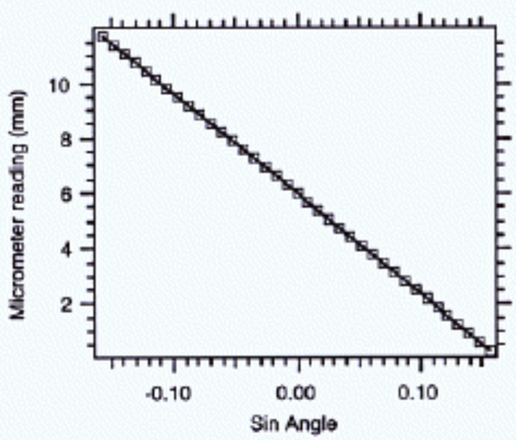

FIG. 1. Micrometer reading versus corresponding sin Angle. This graph is used to calibrate the micrometer readings recorded to sin angles. The slope is $(-36.503 \pm 0.003)mm$.

The angle change is calculated from:

$$\theta = \sin^{-1}\left(\frac{\mu}{\text{slope}}\right) \qquad (3)$$

Where μ is the measured experimental micrometer reading and the slope from Figure 1, $(-36.503 \pm 0.003)mm$.

The error in θ is found from:

$$\frac{\delta\theta}{\theta} = \sqrt{\left(\frac{\delta\mu}{\mu}\right)^2 + \left(\frac{\delta\text{slope}}{\text{slope}}\right)^2} \qquad (4)$$

Where $\delta\theta$ is the error in the angle, $\delta\mu$ is the standard deviation of the five micrometer readings measured for each amperage and δslope is the deviation of the slope from Figure 1, ±0.003mm.

The magnetic field for each amperage is variable depending upon the distance an object is from the magnetic poles. The glass cube is (3.85 ± 0.01) cm wide and the distance between the poles is approximately 4.15 cm Since the cube covers almost the entire distance between the poles, the average magnetic field on the cube is the average magnetic field between the poles at each amperage. If the magnetic field is measured at two amperages far apart, 8 Amps and 3 Amps, it is possible to find a constant that can determine the average magnetic field for every other amperage. The data for the magnetic field at 8 Amps and 3 Amps as a function of position between the poles is shown in Figure 2.

An average of the magnetic field at 8 Amps was calculated as was an average of the magnetic field at 3 Amps. The average magnetic fields at 8 Amps is $(6.55 \pm 0.77)kGauss$ and at 3 Amps is $(2.37 \pm 0.24)kGauss$ both are seen in relation to the graphs of their magnetic field lines in Figure 2. There may be error due to the magnetic field probe which drifts at different temperatures. Applied Magnets Laboratory states that the probe drifts 2% for each degree above or below 25 degrees Celsius.

The constant that determines the average magnetic field at other amperages is calculated from:

$$B_{\text{const}} = \frac{B_8}{\text{AveB}_8} = \frac{B_3}{\text{AveB}_3} \qquad (5)$$

Where B_8 and B_3 are the magnetic fields found at the lowest value for each magnetic field, AveB_8 and AveB_3 are the average magnetic fields for 8 Amps and 3 Amps respectively. The B_{const} is 0.87 ± 0.44. This constant is the same for all currents, shown by Figure 3.

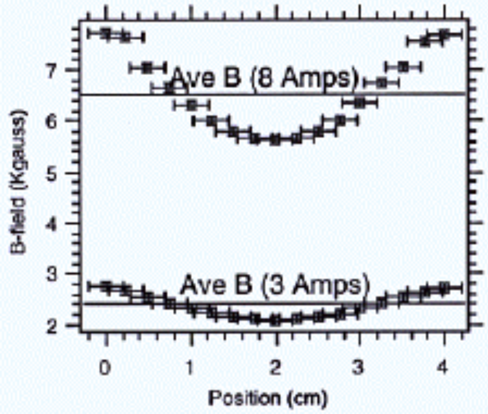

FIG. 2. The lower plot is of the magnetic field at 3 Amps verses the position between the magnetic poles. The top plot is of the magnetic field at 8 Amps verses the position between the magnetic poles. The graph for both amperages has a similar shape. The error bars are due to the significant figures in the gauss meter and the graph paper used to measure the distance.

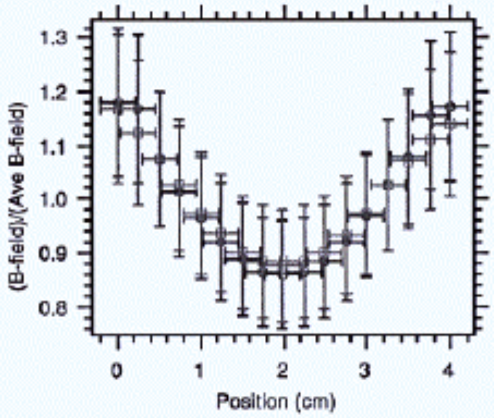

FIG. 3. This graph overlays the data for 3 Amps and 8 Amps once each magnetic field value is scaled by the average of that magnetic field. This shows that the average magnetic field for all other amperages will have the same values as these if the points of the magnetic field are scaled by the average of the magnetic field. The average magnetic field for other amperages is found from one point of the magnetic field.

Micro-meter Ave	Std. dev. micro.	Current (Amps)	Angle (Min.)	Dev min	Ave B (kgauss)	Dev of B
5.13	0.06	0	484	5.45	0.02	0
5.42	0.05	0.5	512	4.98	0.22	0.03
5.7	0.05	1	539	4.9	0.63	0.07
5.93	0.02	1.5	561	2.28	1.05	0.12
6.24	0.05	2	591	4.56	1.47	0.17
6.57	0.05	2.5	623	4.47	1.9	0.22
6.91	0.05	3	655	4.9	2.37	0.28
7.26	0.02	3.5	688	1.82	2.76	0.32
7.53	0.03	4	714	3.15	3.23	0.38
7.8	0.05	4.5	740	4.53	3.64	0.43
8.08	0.02	5	768	1.83	4.04	0.48
8.42	0.03	5.5	800	2.9	4.54	0.53
8.72	0.02	6	830	1.97	4.97	0.58
9.06	0.04	6.5	862	4.28	5.39	0.63
9.34	0.02	7	890	1.73	5.85	0.69
9.67	0.02	7.5	922	1.9	6.25	0.74
10.01	0.03	8	955	2.65	6.56	0.77
10.3	0.04	8.5	983	3.61	7.08	0.83
10.46	0.03	9	999	2.65	7.4	0.87

TABLE I: Under Micrometer reading are the values measured from the micrometer when the least intensity is present at each of the currents measured. The second column is the standard deviation of those micrometer readings. The current is where the current was set for each data run to create a change in magnetic field. The angle in minutes is what the measured micrometer reading data was converted to using Figure 1, shown as the y axis in Figure 4. The deviation of the angle is found from equation 3. The ave B, or magnetic field, is found from measuring the magnetic field at each amperage and converting that to an average with equation 5, shown as the x axis in Figure 4.

To calculate the Verdet constant the change in the angle (in minutes) verses the change in the magnetic field (kgauss) is plotted to find the slope, in Figure 4.

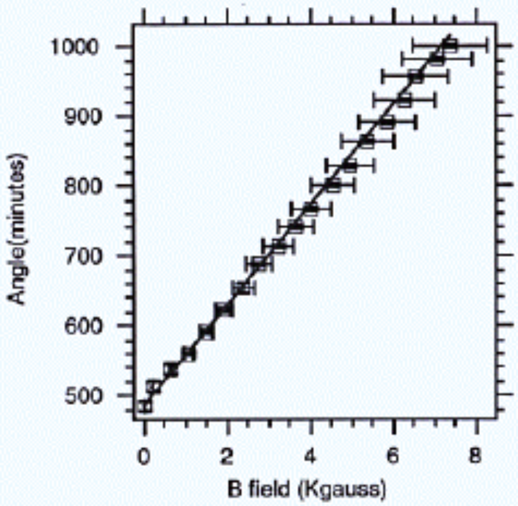

FIG. 4. This calculates the Verdet constant. The line fit is weighted to the error bars therefore giving a slope of $(71.5 \pm 7)\,\mathrm{min}/\,Kgauss$.

ANALYSIS AND INTERPRETATION

The slope is $(71.5 \pm 7)\,\mathrm{min}/\,Kgauss$. The width of the glass is $(3.85 \pm 0.01)cm$. This gives a Verdet constant of $(18.6 \pm 1.8) \times 10^{-3}$ min/(cm*gauss). The book value[2] for the Verdet constant for phosphate crown glass is (16.1×10^{-3}) min/cm*gauss. But the value for the Verdet constant can vary depending upon the temperature, this may cause some discrepancy. The actual composition of the glass used is unknown but it is believed to be phosphate crown glass by comparing the Verdet constants of different types of glass.[2] The polarization of light subjected to a magnetic field is proportional to the change in that magnetic field and the thickness of the substance traversed.

CONCLUSION

The Verdet constant was found for phosphate glass using the Faraday effect and the theory derived by Lorentz. The value for the Verdet constant is $(18.6 \pm 1.8) \times 10^{-3}$ min/(cm*gauss). The Verdet constant measured is similar to only one other Verdet constant seen by others and that is phosphate crown glass. Due to the large difference between Verdet constants for different types of glass it is believed that the glass experimented with is phosphate glass or some mixture of it.[2] Unfortunately the measured value of the Verdet constant is not within the standard deviation limit. This is most likely due to the fact that the Verdet constant depends on temperature and also depends on the wavelength of the light we used. The light used has a wavelength of 632.8 nanometers and the standard value uses a light with a wavelength of 589.3 nanometers. Neither the temperature nor the wavelength errors were accounted for.

[1] J.J. Lamor, Aether and Matter, (Cambridge University Press, 1900) P352.

[2] Charles D. Hodgman, Handbook of Chemistry and Physics, 31st Edition, (Chemical Rubber Publishing Co., Cleveland, Ohio, 1949).

[3] Francis A. Jenkins and Harvey E. White, Fundamentals of Optics, (McGraw-Hill Book Company, Inc., New York, 1950).