

Measurement of Verdet Constant in Diamagnetic Glass Using Faraday Effect

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ABSTRACT

Many materials exhibit what is called circular dichroism when placed in an external magnetic field. An equivalent statement would be that the two circular polarizations have different refractive indices in the presence of the field. For linearly polarized light, the plane of polarization rotates as it propagates through the material, a phenomenon that is called the Faraday effect. The angle of rotation is proportional to the product of magnetic field, path length through the sample and a constant known as the Verdet constant. The objectives of this experiment are to measure the Verdet constant for a sample of dense flint glass using Faraday effect and to compare its value to a theoretical calculated value. The experimental values for wavelength of 505 and 525 nm are $V = 33.1$ and 28.4 rad/T m, respectively. While the theoretical calculated values for wavelength of 505 and 525 nm are $V = 33.6$ and 30.4 rad/T m, respectively.

Key words: verdet constant, diamagnetic glass, faraday effect

INTRODUCTION

Many important applications of polarized light involve materials that display optical activity. A material is said to be optically active if it rotates the plane of polarization of any light transmitted through the material. The angle through which the light is rotated by a specific material depends on the length of the path through the material and on concentration if the material is in solution. One optically active material is a solution of the common sugar dextrose. However, rotations of polarized light are not only limited to optically active materials, but also including some optically inactive materials exposed to high magnetic field. In magnetized medium the refractive indices for

right- and left-handed circularly polarized light are different. This effect manifests itself in a rotation of the plane of polarization of linearly polarized light. This observable fact is called magnetooptic effect.

Magnetooptic effects are those effects in which the optical properties of certain materials are affected by applied magnetic fields or the material's own magnetization. Magnetooptic effects occur in gases, liquids, and solids. In general, solids exhibit the strongest magnetooptic effects, liquids exhibit weaker effects, and gases exhibit the weakest effects (Weber, 1995). The first magnetooptic effect was discovered by Michael Faraday in 1845 and is now commonly known as the Faraday effect. This phenomenon

occurs when linearly polarized light propagates through a transparent isotropic materials exposed to a magnetic field aligned parallel to the direction of propagation of the light. Under these conditions, the plane of polarization rotates by an amount proportional to the applied magnetic field. This action is known as Faraday rotation. One of the most important properties of Faraday rotation is its nonreciprocal behavior. If light makes two opposite passes through a magneto-optic material, the Faraday rotation does not cancel but rather doubles (Weber, 1995; Zvezdin and Kotov, 1997). This property distinguishes the effect from optical activity in which reflecting the light back through the material cancels the polarization rotation observed in a single pass through the material.

Later on, in 1854, Verdet found that the angle of rotation θ is proportional to the length l of the path in the material and the magnetic flux density H . This rotation may be expressed by relation

$$\theta = VHI, \quad (1)$$

where V is the Verdet constant for the material. The Verdet constant is defined as the rotation per unit path, per unit field strength. It depends upon the properties of the medium, frequency of light, and the temperature. In fiber optic magnetic sensors based on Faraday effect, the Verdet constant is a measure of the strength of the Faraday effect in the fiber (Udd, 1991).

Solid magneto-optic materials are the

most commonly used today for sensor applications. Solids are classified into the class of diamagnetic, paramagnetic, ferromagnetic, antiferromagnetic, and ferrimagnetic materials. Diamagnetic materials generally offer lower Verdet constant, hence lower measurement resolution, but they have better environmental stability, particularly temperature stability. On the other hand, paramagnetic and ferromagnetic materials are less environmentally stable but generally have much higher Verdet constant. For that reason, diamagnetic materials, especially diamagnetic glasses in bulk and fiber form, are commonly chosen as the sensing element in high stability Faraday effect sensors (Williams *et al.*, 1991; Martinez *et al.*, 2005). Therefore, the purpose of this present work is to measure the Verdet constant for the diamagnetic glass using Faraday effect and compare it to a theoretically calculated value.

MATERIALS AND METHODS

To check the Verdet constant for the diamagnetic glass, Schott's SF 6 glass, which is a dense flint containing over 70% by weight lead oxide, was used as a sample. It is commonly used in current sensor and X-ray protective spectacles. The experimental set up of the dynamic method for monitoring the Faraday effect in glass is schematically illustrated in Figure 1.

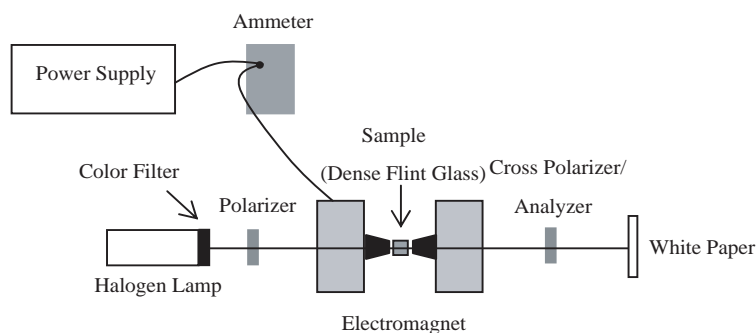


Figure 1 Optical system for estimation of Verdet constant.

The 50 W experimental lamp is supplied by the 12 V AC voltage source. The DC output power supply is variable between 0 and 20 V DC and is connected via an ammeter to the coils of the electromagnet which are in series. Accordingly, relationship between the current and the magnetic field throughout the sample can be able to explore. The electromagnet needed for this experiment was constructed from a laminated U-shaped iron core, two 600-turn coils and the drilled pole pieces, the electromagnet then being arranged in a stable manner on the table. To resolve the Verdet constant for 30 mm long flint glass cylinder, it was inserted in the pole piece holes. The electromagnets produced a non-uniform magnetic field throughout the space in which the sample was placed. As a result, the distribution of the magnetic flux-density was determined in the space between the pole pieces at first. Using the axial probe of the teslameter, the flux-density was measured along the whole gap in steps of 5 mm. The procedure was repeated for different currents at 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5 and 4.0 A, respectively. These results were then used to evaluate an average magnetic field experienced by the sample.

In Figure 1, the light from halogen lamp was filtered by color filters. The wavelength of 505 nm and 525 nm were passed and used in this experiment. After that, it passed through a polarizer, the magnets with the sample in the center and through the analyzer. A sheet of white paper placed close to the analyzer was used to help to detect the minima of transmitted light. If the polarizer and analyzer are crossed, the translucent screen image appears dark. It brightens up when the coil current is switched on and a longitudinal magnetic field is generated between the pole pieces. At each current value, from 0.5 A to 4 A, the rotation of the plane of polarized light would be considered by the cross-polarizer by adjustment of the analyzer through a certain angle θ produces maximum extinction of the light that could be

observed on the white paper. If the direction of the magnetic field is reversed by changing the polarity of the coil current, the analyzer must be adjusted in the opposite direction in order to darken the brightened field of view again. So the experiments were repeated with the opposite magnetic field direction after reversing the polarity of the coil current.

For perusal the Verdet constant of diamagnetic glass, it can be found in the following way. In diamagnetic materials, which have no macroscopic or microscopic magnetization in the absence of an applied magnetic field, the Faraday effect arises from the splitting of the upper level of an optical transition into right and left circularly polarized components. The refractive indices, n_+ and n_- , for the right-hand and the left-hand circularly polarized waves, respectively, are equivalent in the absence of a magnetic field. When the linearly polarized light passes through a diamagnetic material, parallel to the direction of the applied magnetic field H , n_+ and n_- diverge, causing the two polarizations to propagate with different velocities and phases (Ruan *et al.*, 2005). As a consequence, the plane of polarization of the linearly polarized light rotates through the angle

$$\theta = \frac{\omega}{2c}(n_+ - n_-)l = VHL, \quad (2)$$

where ω is the angular frequency, c is the velocity of the light, l is the path length of an optical beam in the medium, and V is defined as expressed in Eq. (1).

The magnetic-field induced Larmor precession of electron orbits is the simplest mechanism for the Faraday effect. Instead of one eigenfrequency of the electrons (ω), two resonance frequencies (ω_+ and ω_-) arise, corresponding to the right-hand and the left-hand circular oscillations when there is a magnetic field in the medium. The difference between the resonance frequencies ω_+ and ω_- results in a displacement of the curves $n_+(\omega)$ and $n_-(\omega)$ relative to each other on the frequency scale:

$$n_{\pm}(\omega) \approx n(\omega) \pm \frac{db}{d\omega} \frac{eH}{2mc} \quad (3)$$

where e and m are the electron charge and mass, respectively, and $n(\omega)$ is the refractive index of the material in the absence of the field H . Substitution of Eq. (3) into (2) yields the well-known Becquerel formula

$$V = \frac{e\lambda}{2mc} \left(\frac{dn}{d\lambda} \right), \quad (4)$$

where λ is the wavelength of light. Eq. (4) indicates that the Verdet constant is linearly proportional to both the wavelength of the light and to the dispersion $\frac{dn}{d\lambda}$ of the medium.

RESULTS AND DISCUSSION

In the absence of a flint glass SF6 cylinder, the distribution of the magnetic flux-density in the space between the pole pieces was investigated. It was found that the flux density increases strongly to the center of the gap and decreases to either side. These results are shown

in Figure 2. Starting from the maximum flux-density in the gap, a mean flux-density to the test specimen for any coil current is easily attributed.

Since electromagnets were used to generate the magnetic field for this experiment, a correlation between the current supplied to the electromagnets and the average magnetic field in the space between the poles could be obtained by the curve fitting method. A linear curve was fit to the average magnetic field versus applied current as shown in Figure 3. This relation was represented by equation:

$$H = 35.496 I. \quad (5)$$

This equation was used to convert the applied current into average magnetic fields.

In order to see how much the polarized beam is rotated as a function of the magnetic field strength, the relationship between the angle of rotation (2θ) and the current applied to the electromagnets was inspected. Figure 4 shows the angle 2θ as a function of the average magnetic field for wavelength of 505 nm and 525 nm. The equations that fit the angle 2θ versus average

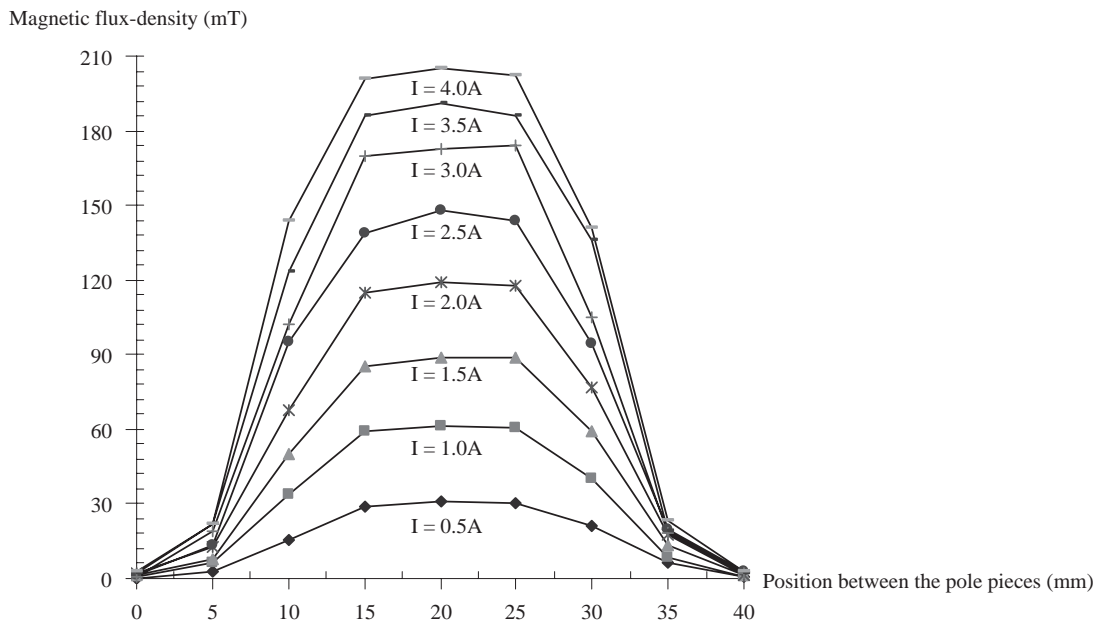


Figure 2 Flux-density distribution between the pole pieces for difference coil currents.

magnetic field for wavelength of 505 nm and 525 nm are $2\theta = 0.114$ and $2\theta = 0.090H$, respectively. The Verdet constant can be calculated from the slope of the line divided by $2l$. From the results, they could be concluded that the Verdet constant for dense flint glass at 505 and 525 nm are 33.1 and 28.4 rad/T m, respectively. Theoretically, the Verdet constant can be calculated from Eq. (4). This equation can be represented by the following empirical expression:

$$V(\lambda) = \frac{\pi}{\lambda} \frac{n^2(\lambda) - 1}{n(\lambda)} \left(A + \frac{B}{\lambda^2 - \lambda_0^2} \right) \quad (6)$$

where A is 15.7116×10^{-7} rad/T,
 B is 6.3430×10^{-19} m²·rad/T,
 $n(\lambda)$ is index of refraction at a given wavelength,
 and λ_0 is 156.4 nm.
 The indices of refraction at 505 and 525 nm are given from Schott Optical Glass.

Average magnetic field, H (mT)

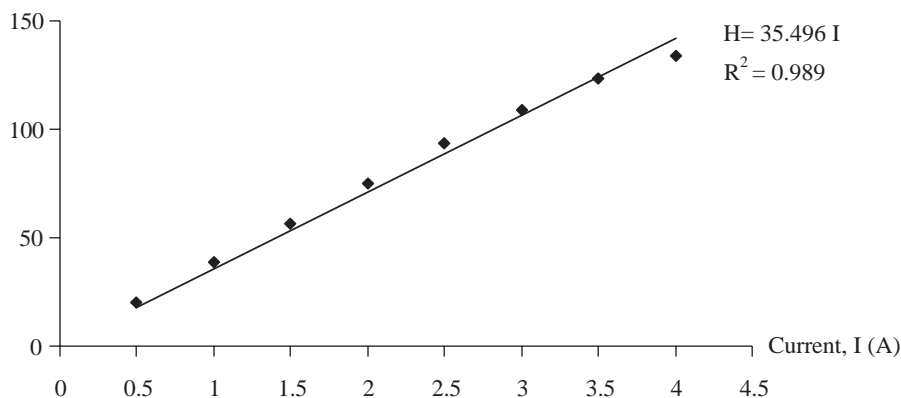


Figure 3 Graph of current through electromagnets versus average magnetic field generated as a result of the current flow.

2θ (degree)

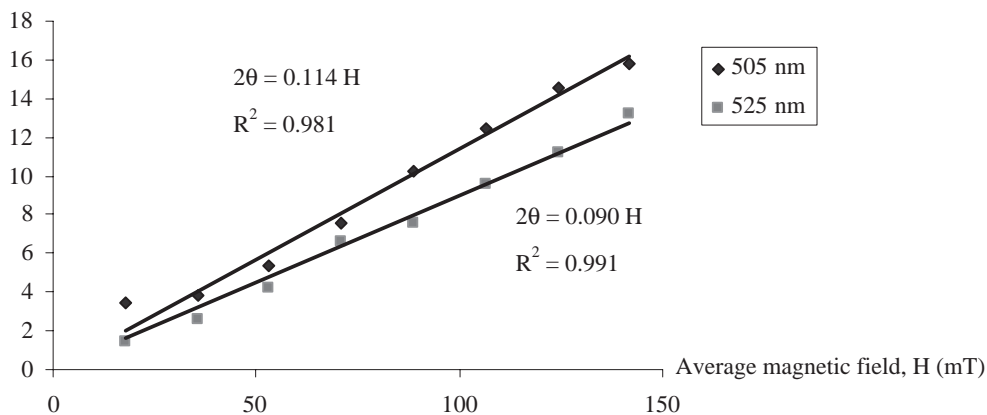


Figure 4 Angle of rotation of the polarization-plane as a function of the average magnetic field for $\lambda = 505$ nm and 525 nm.

Substituting all parameters into Eq. (6), the theoretical Verdet constant are revealed. For 505 nm, this theoretical value is 33.6 rad/T m. For 525 nm, this theoretical value is 30.4 rad/T m. The percentage errors of Verdet constant from this experimental are less than 6.5%.

CONCLUSIONS

This experiment shows the measurement of the Verdet constant for the diamagnetic glass using Faraday effect. However, in the future, the Faraday effect could be explored in a number of different ways. One way is to choose a different sample such as a liquid, for which the Verdet constant is known and find a way to increase the accuracy and precision of the apparatus used in order to get better experimental values. Furthermore, temperature dependence of the Verdet constant in diamagnetic glass should be determined because it may be significant in certain applications, such as high accuracy sensors. The relative change in Verdet constant with temperature using the Becquerel equation can be expressed as

$$\frac{1}{V} \frac{dV}{dT} = \frac{\frac{d}{dT} \left(\frac{dn}{d\lambda} \right)}{\left(\frac{dn}{d\lambda} \right)} = \frac{\frac{d}{d\lambda} \left(\frac{dn}{dT} \right)}{\left(\frac{dn}{d\lambda} \right)}. \quad (7)$$

Besides measuring the Verdet constant of another material, measuring the index of refraction of material is also interesting if knowing its Verdet constant and using the different wavelengths of light to $\lambda \frac{dn}{d\lambda}$ determine.

LITERATURE CITED

- Martinez, L., F. Cecelja and R. Rakowski. 2005. A Novel Magneto-optic Ferrofluid Material for Sensor Applications. **Sensors and Actuators A**. 123-124: 438–443.
- Ruan, Y., R.A. Jarvis, A.V. Rode, S. Madden and B.L. Davies. 2005. Wavelength Dispersion of Verdet Constants in Chalcogenide Glasses for Magneto-optical Waveguide Devices. **Optics Communications** 252: 39-45.
- Udd, E. 1991. **Fiber Optic Sensors: An Introduction for Engineers and Scientists**. John Wiley & Sons, Inc., New York.
- Weber, M.J. 1995. **CRC Handbook of Laser Science and Technology**. Vol. V. Part 3. CRC Press, Boca Raton.
- Williams, P.A., A.H. Rose, G.W. Day, T.E. Milner and M.N. Deeter. 1991. Temperature Dependence of The Verdet Constant in Several Diamagnetic Glasses. **Applied Optics** 30: 1176-1178.
- Zvezdin, A.K. and V.A. Kotov. 1997. **Modern Magneto-optics and Magneto-optical Materials**. Institute of Physics Publishing, Bristol.