

A New Faraday Rotation Measurement Method for the Study on Magneto Optical Property of PbO-Bi₂O₃-B₂O₃ Glasses for Current Sensor Applications

Qiuling Chen, Qiuping Chen, Shuangbao Wang

Department of Materials Science and Chemical Engineering, Politecnico di Torino, Torino, Italy

E-mail: Qiuling.chen@polito.it

Received August 17, 2011; revised September 19, 2011; accepted September 28, 2011

Abstract

MAGNETO-OPTICAL current transformers (MOCT) based on the Faraday Effect provide numerous advantages over the conventional transformers. However the commonly used materials in MOCT are crystals that are very expensive and temperature dependence thus will cause many problems for the output signal. Cost efficient diamagnetic PbO-Bi₂O₃-B₂O₃ (PBB) glass system is fabricated in this study, for the aim of obtaining a good candidate glass with high Verdet constant and good temperature resistance to replace crystals. A home-made optical bench was setup, calibrated and used for measuring the Verdet constant of the fabricated glasses. Glass with composition of 50%PbO-40%Bi₂O₃-10%B₂O₃ in mol showed high Verdet constant (0.1533 min·G⁻¹·cm⁻¹) and good value of the figure of merit (0.02635 min·G⁻¹), which can be considered as the ideal candidate for MOCT applications.

Keywords: MOCT, Magnetic Optical Glass, Verdet Constant

1. Introduction

MAGNETO-OPTICAL current transformers (MOCT's) based on the Faraday Effect provide numerous advantages over the conventional transformers. The measurements are contactless, small volume and cost efficient. It is hopeful for MOCT can find much wider applications especially in automobile industry [1,2]. However commonly used materials for MOCT are crystals which are very expensive and temperature dependence [3,4]. On the other hand, low cost glass with good optical-magnetic properties (e.g. high Verdet constant and figure of merit etc.) is required greatly [5-7].

Literatures on glasses based on heavy metal oxides for the above application have been reported [1,2]. Especially the oxide glasses with lead and bismuth oxides, due to the big mass and polarizability of ions Pb²⁺ and Bi³⁺ belong to diamagnetism glass and has good temperature resistance, smaller phonon energy and larger refraction indices [2,4] comparing to borosilicate, phosphate and silicate glasses. Based on previous study carried out by the authors [1,5], a PbO-Bi₂O₃-B₂O₃ (PBB) based glass system was chosen for this study with the aim of obtaining a good candidate for MOCT design.

Concerning the measurement of Faraday rotation, the conventional double light way method is complex due to the use of lock-in amplifier and computer assisted detector system and so on [8,9]. In this study, a home-made single light way method was setup, calibrated and used to measure the Verdet constant of the glass, the advantage of this optical bench is single and low cost: no needs the lock-in amplifier, the detector is a power meter. The magnetic field is induced by solenoids on which the current will be applied by a DC supplier. Through the optical bench, the magneto optical properties of the glasses were studied.

2. Experiments

2.1. Glass Fabrication and Characterization

The compositions of the prepared glass are listed in **Table 1**. Synthesis was carried out in ceramic crucibles in an electric oven at the temperature at around 900°C followed with stirring during melting. The melted mass was poured into a cast brass form and then relief annealed. Samples used for studies were cut into $\phi 10$ mm \times 2 mm slides and polished using Logitech PM5. From

many samples of different percentage of oxides, the one with optimum composition assuring the best optical and magnetic properties was chosen.

The refractive indexes of samples were measured using a prism coupling method (Meticon Model 2010 M). The absorption spectra in ultraviolet-visible region (200 - 2000 nm) were recorded for each sample using a UV-Visible-IR spectrophotometer (Varian Cary 500). Optical energy gap for the studied glasses were evaluated from relation $(\alpha h\nu)^{1/2} = B^{1/2}(h\nu - E_g)$, where $B^{1/2}$ is the slope of the absorption edge reflecting the sample disorder [10,11] and $h\nu$ is the photon energy. On the absorption edge the slope line was extended and cross onto horizontal axis (wavelength), the crossing-point means the absorption threshold wavelength.

Raman spectra were measured using a MKI Renishaw Raman spectroscopy equipped with a BH2-UMA Olympus microscope between 200 cm^{-1} to 2000 cm^{-1} .

2.2. Faraday Effect Measurements on Glasses

2.2.1. Optical Bench Setup

Figure 1 schematically shows the setup for the Verdet constant measurement. In order to investigate the Faraday Effect of the fabricated PBB glasses, a home-made Faraday Effect test apparatus is built up: a He-Ne laser with 15 Mw power at 632.8 nm wavelength was used as the light source, a 100% reflection mirror was used to change the light way to a polarizer which polarized the incident light beam to pass the glass which was placed in a 320 turns solenoid. The polarizers, solenoids and powermeter detector are integrated in a dark box (dotted line) to avoid the background light and reduce the noise (two polarizers were set in 90° to each other in orientation).

2.2.2. Measurement and Calculation

Due to the Faraday rotation, an angle will happened under the magnetic field B, the output intensity of the current is different from that of without B. The difference between

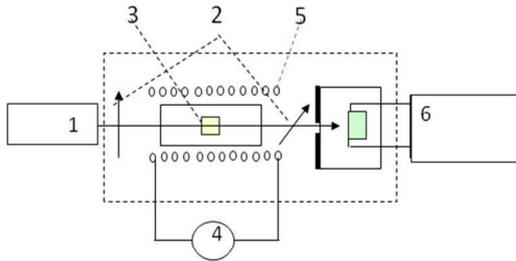


Figure 1. Schematic diagram of optical bench set-up for Faraday rotation measurement, 1. He-Ne Laser; 2. Polarizers; 3. Bulk glass; 4. DC supplier; 5. Solenoid; 6. Power meter.

the two values is named ΔI . The I , I_0 , the rotated angle θ , and the Verdet constant of glass V , meet the following relationship:

$$I = I_0 \cos^2(a + \theta) \quad (1)$$

$$\Delta I = I_0 \sin^2(\theta) \propto I_0 \theta^2 \quad (\text{while } a = 90^\circ) \quad (2)$$

$$q = VBL \quad (3)$$

$$B = \mu_0 NI / L_s \quad (4)$$

where I is the detected transmission light intensity without magnetic field, I_0 is the original incident light intensity with the magnetic field applied, a is the angle between two polarizers without magnetic field, L is the sample length, μ_0 is the constant ($1.26 \times 10^{-6} \text{ B}\cdot\text{m}^{-1}$), N is the turns of solenoids, I is the applied current, L_s is the length of solenoids. Through the detected output light intensity (I and I_0), the rotated angle θ could be obtained according to Equations (1) and (2). B could be obtained through the Equation (4). And according to Equation (3), the V can be calculated.

2.2.3. Uniformity Test of Magnetic Field

The magnetic field B was induced by the DC supplier. The current was set as 1A DC, and the light intensity I and I_0 , represented the output voltage values from detector before and after the switch on of the DC circuit, respectively; through the switch on and off the current, a magnetic field will be induced or disappeared in the solenoid.

The uniformity and homogenous of B inside the solenoids was tested using the magnetometer. The length of solenoid is around 0.2 m. The B in every one centimeter from the middle of the solenoid to two ends was measured using magnetometer. **Figure 2** shows the distribution profile of the B in different position of the solenoids. It can be seen that the inner magnetic field of solenoid is uniform.

The relationship between applied current I and the change of B also was measured for the aim of verify the uniformity of B inside the solenoids. Changing the applied current, different B in the middle of solenoid was obtained from magnetometer. **Figure 3** shows the changes of B under different current I . The relationship between them is a linear which proved again the B inside the solenoids is homogenous and uniform.

2.2.4. Calibration of Optical Bench

Calibration of the set up was performed using a standard pure silica sample (its Verdet Constant = $0.01352 \text{ min}\cdot\text{G}^{-1}\cdot\text{cm}^{-1}$ from literatures [9]). Every time before measuring the glasses, under the same condition the pure silica was put inside the solenoids, with and without B , the output of intensity of current was recorded and calcula-

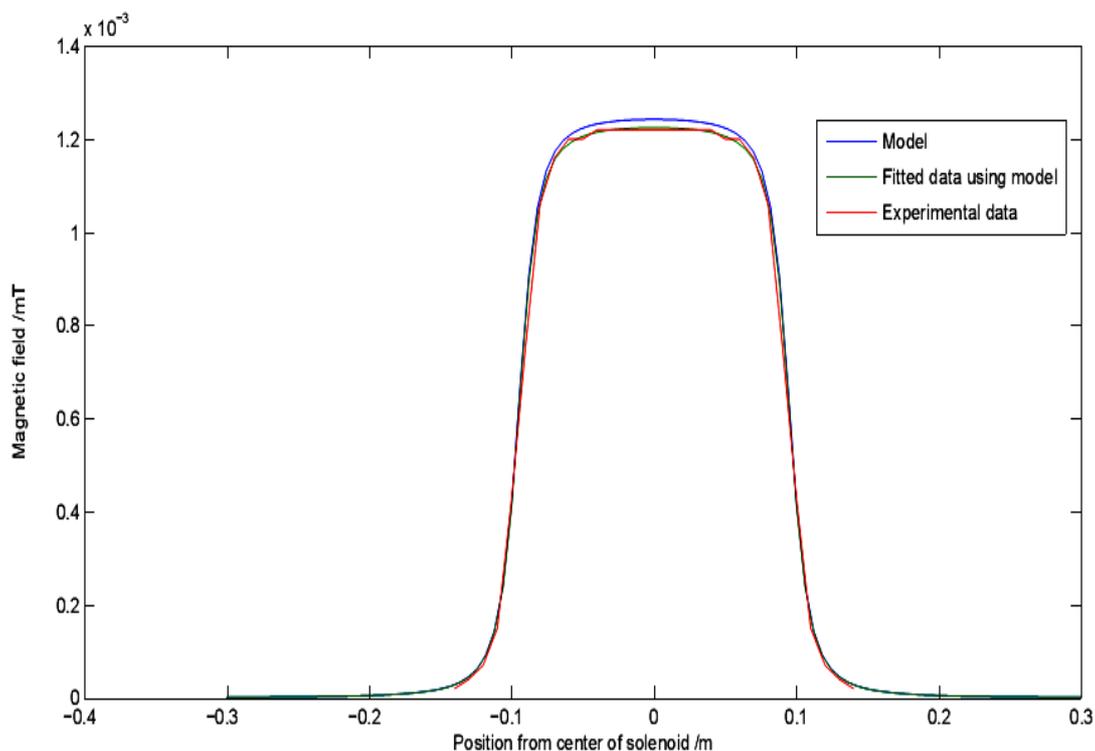


Figure 2. Distribution profile of the B in different position of the solenoids.

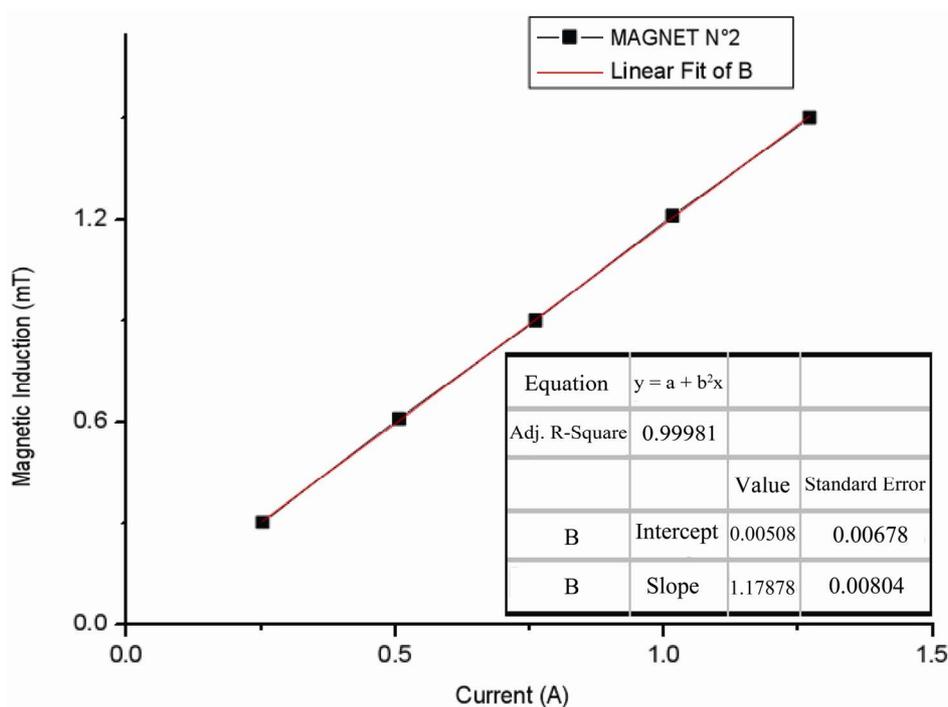


Figure 3. Magnetic field B vs current I.

ted. Compare to its value of $0.01352 \text{ min}\cdot\text{G}^{-1}\cdot\text{cm}^{-1}$, if the measured value is not exceed 0.001 error rate, this proved that the optical bench is ok for use.

3. Results

Table 1 reports the composition of prepared glasses and

Table 1. Magnetic-optical properties of the PBB glass samples.

Glass	PBB01	PBB2	PBB03	PBB4	PBB5	PBB06
Composition*	50-40-10	40-50-10	20-70-10	35-45-20	15-65-20	5-35-40
V (min·G ⁻¹ ·cm ⁻¹)	0.1533	0.1153	0.1105	0.083	0.083	0.0505
Cutoff (nm)	474.85	471.27	469.84	448.38	458.39	406.16
Q (min·G ⁻¹)	0.026	0.016	0.015	0.014	0.014	0.012
T _g (°C)	289	293	292	307	315	327
T _x -T _g (°C)	81	63	61	100	58	101
n @633nm	2.374	2.357	2.139	2.215	2.059	2.002
ρ (g/cm ⁻³)	8.33	8.33	8.31	7.85	8.03	6.57

*Composition of PBB is in mol: PbO-Bi₂O₃-B₂O₃.

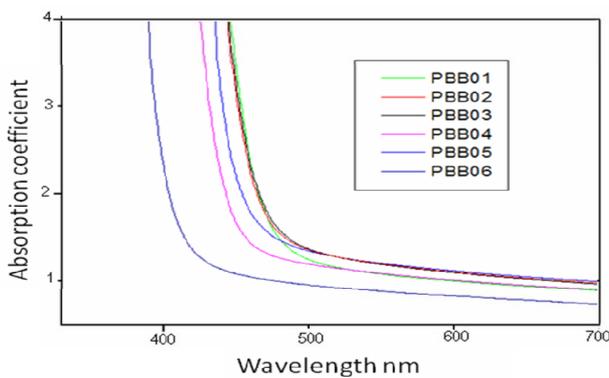
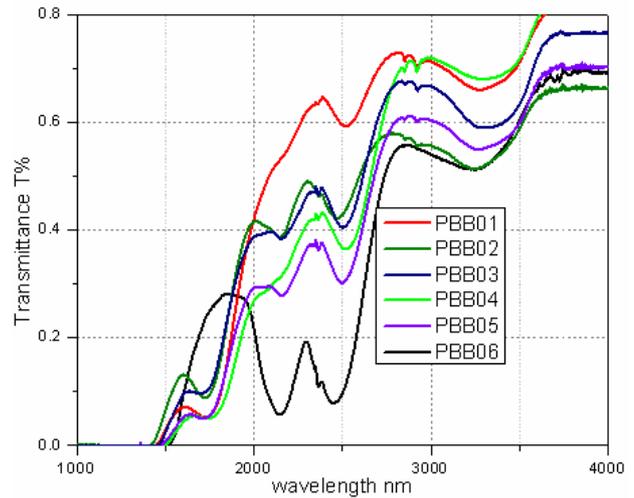
their thermal and magneto optical properties, including the T_g, refractive index, Verdet constant, cutoff, the figure of merit and so on. The difference of T_x and T_g is usually used to evaluate the thermal stability of the glasses, generally speaking, the bigger the difference, the more stable of the glass.

3.1. UV-Vis and FT-IR Spectra Analysis

Figure 4 shows the absorption spectra in the UV-visible region of all glasses. The absorption coefficient, cutoff changed strongly with the glass composition. The cutoff shifted to longer wavelength with the increasing of total amount of PbO + Bi₂O₃. Glass PBB01 showed the biggest cutoff and lower absorption compared with other samples. **Figure 5** shows the FT-IR spectra analysis on the prepared glasses. PBB01 showed more than 70% of transmittance during 2000 nm to 4000 nm. The peak around 3300 nm is due to the OH absorption. With the increase of PbO and Bi₂O₃ content, the spectrum exhibits a shift to longer wavelength.

3.2. Verdet Constants and the Figure of Merit

The magnetic optical property of fabricated glasses is

**Figure 4. UV-visible absorption spectra of the PBB glasses.****Figure 5. FT-IR transmittance spectra of the PBB glasses.**

evaluated in term of Verdet constant V and the figure of merit Q. The relationship between V and Q is: $Q = V/\alpha$, where α is the absorption coefficient which was obtained from **Figure 4**. **Table 1** reports the Verdet constant for all the glass samples, along with their cutoff and figure of merit. **Figure 4** shows the relationship between Verdet constant and the cutoff. The PBB01 showed the highest value of Verdet constant e.g. 0.1533 min·G⁻¹·cm⁻¹, the largest cutoff wavelength of 474.85 nm and the best Q of 0.02635 min·G⁻¹.

3.3. Raman Spectra

The change of glass properties is due to the change of glass structures. **Figure 7** reports the change of structures for all samples. There are mainly five peaks named as, A (400 cm⁻¹), B (550 cm⁻¹), C (710 cm⁻¹), D (920 cm⁻¹) and a broad band (E) around 1220 cm⁻¹. A significant change in spectrum both for the shape and intensity was observed. PBB01 showed the highest intensity of peaks for A (400 cm⁻¹) and B (550 cm⁻¹), and PBB06 showed the lowest intensity of the same peaks.

The presences of different peaks for heavy metal oxides glasses at different wavelength, for example, 300 - 600 cm⁻¹, especially vibrations between 380 - 580 cm⁻¹ due to the bridging anion modes, and 650 - 950 cm⁻¹ due to the non-bridging anion modes [12]. Bismuth and lead cations have similar atomic weight, they have similar polarization behaviors. The peak A and B in **Figure 7** correspond to the "bridge-anion" motion due to symmetric stretch motion of Bi-O-Bi and Pb-O-Pb bridges combined with some Bi-O-Pb.

A broadening at around 1250 cm⁻¹ which is named as E peak is attributed mainly to trigonal boron [BO₃] [13, 14]. With the change of content of B₂O₃ in the glass, a

slight change for the peak E was also observed.

4. Discussion

Samples with different compositions presented different thermal and magneto optical properties as showed previously. The Verdet constant of the glasses, which was measured using the home-made optical bench, has relation with the composition, energy gap and cutoff of the glasses.

4.1. Relationship between Verdet Constant and Composition

It is know that the Verdet constant of a magnetic-optical material is related to the electron shell structure of the atoms in the transparent medium. If the ions have the electron structure same with inert gas, the applied field can induce the Zeeman splitting on the ion energy levels. The resulting rotation of the polarized plane is diamagnetism, and the rotating angle θ is positive; the applied field can induce the moment of force of electrons change in the ions which have unpaired electrons. Basing on the classical electromagnetism theory [15,16], Bacquerel has proposed the relationship between the Verdet constant of a diamagnetic material and the properties of the materials as shown in the following equation:

$$V = (e/2mc)\lambda \frac{dn}{d\lambda} \quad (5)$$

Here, V is the Verdet constant, n is the refraction index of the material; $dn/d\lambda$ is the dispersion of the material; e is electron's electrical quant, m is the electron mass, c is light speed and λ is the corresponding light wavelength. From this Equation (5), it can be seen that Verdet constant of the diamagnetic material becomes higher when the dispersion of the material increases. In fact, the presence of heavy metal ions such as Pb^{2+} , Bi^{3+} in the glasses could contribute greatly to the color dispersion of the glasses. Therefore, the increase of the total amount of these ions in the glasses will not only lead to the shift of their cutoff, but also the increase of Verdet constant.

Basing on the quantum theory [7,15] the Verdet constant of the diamagnetic material is also related to the ion carriers with energy level splitting possibility as demonstrated in the following formulary (6):

$$V = (4\pi Nv^2) \sum_n \left[A_n / (v^2 - v_n^2)^2 \right] \quad (6)$$

Here N is the carriers in per unit volume; v : frequency of the incident wave; v_n is the frequency of electrons migration; A_n is parameters correlative with migration intensity.

The formulary (6) shows that the Verdet constant of a diamagnetic material is related to the carriers' concentration N , in the case of this study, the Pb^{2+} and Bi^{3+} ions are the carriers. Therefore glasses containing higher density of Pb^{2+} and Bi^{3+} ions such as PBB01 will show higher Verdet constant.

From the formulary (6), it is also noted that the Verdet constant of a diamagnetic material has no relationship with the working temperature. This is ideal for MOCT, which makes this PBB glass have great advantages over the currently used crystal for MOCT.

4.2. Relationship between Verdet Constant and Energy Gap

From **Figure 6** and **Table 1**, it can be seen that the Verdet constant also has relationship with cutoff, and the cutoff of glass is related to the energy required for the electron transition of glass network former from unexcited states to excited states. Therefore the shift of cutoff for PBB glasses depended strongly on the change of the total amount of $PbO + Bi_2O_3$ in the glass, which in fact act as both glass network former and modifiers [1,5]. On the other hand, with the decrease of B_2O_3 content which acts as glass network former, the glass network structure will be significantly modified, as it can be seen also from the Raman Spectra in **Figure 7**. In fact, heavy metal ions such like Pb^{2+} , and Bi^{3+} play important roles in the glass as network modifiers that weaken the bridged O-B bonds. With increasing of $PbO + Bi_2O_3$ content, an increase of structural disorder occurred (the PbO could also behavior as network formers, considering the difference between PbO and Bi_2O_3), and various non-bridged centers inside the network will be produced. As a consequence the energy required for breaking down the glass network of OB bond will be decreased which leads to the shift of the cu-

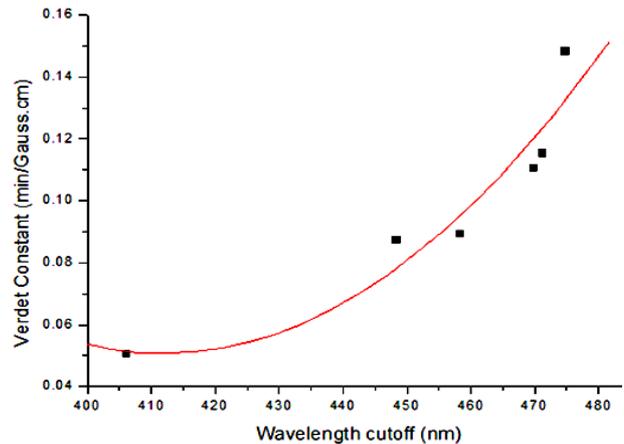


Figure 6. The relationship between the Verdet constant and cutoff.

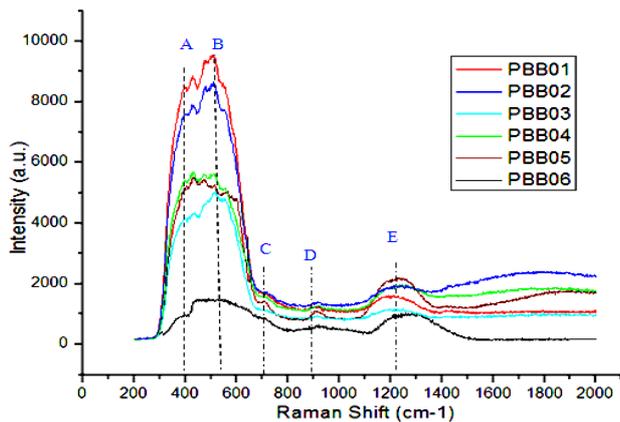


Figure 7. The Raman spectra of PPB MO glasses.

toff towards longer wavelength. Such a shift in cutoff could also be explained by the change of band gap for different constituents in glass systems: it is found that the band gap for B_2O_3 is $E_g(B_2O_3) \approx 8eV$ [17], for PbO is $E_g(PbO) \approx 2.73eV$ [17] and for Bi_2O_3 is $E_g(Bi_2O_3) \approx 2.76eV$ [18]. The increase of $PbO + Bi_2O_3$ and decrease of B_2O_3 in the glass will therefore decrease the band gap of glasses, which means the decrease of energy gap caused the increase of Verdet constant. A similar phenomenon was reported by Y. L. Ruan *et al* [15] for the relationship between Verdet constant and band gap for chalcogenide system glass.

5. Conclusions

A new way for Faraday rotation measurement was used for the study on magneto optical property of PBB glass for MOCT application was carried out. A relationship between Verdet constant and the glass composition has been identified and it is found that with the shift of cutoff of UV absorption to longer wavelength, the Verdet constant of the glasses increased. The optimized glass PBB01 with the composition of $(50\%PbO-40\%Bi_2O_3-10\%B_2O_3)$ shown the largest value of Verdet constant ($0.1533 \text{ min}\cdot\text{G}^{-1}\cdot\text{cm}^{-1}$), and good value of the figure of merit ($0.02635 \text{ min}\cdot\text{G}^{-1}$), which can be considered as the candidate as magneto optical devices application.

6. References

- [1] Q. Chen, M. Ferraris, D. Milanese, *et al.*, "Novel Er-Doped PbO and B_2O_3 Based Glasses: Investigation of Quantum Efficiency and Non-Radiative Transition Probability for 1.5 Mm Broadband Emission Fluorescence," *Journal of Non-Crystalline Solids*, Vol. 324, No. 1-2, 2003, pp. 12-20. [doi:10.1016/S0022-3093\(03\)00223-0](https://doi.org/10.1016/S0022-3093(03)00223-0)
- [2] P. Ripka, "Current Sensors Using Magnetic Materials," *Journal of Optoelectronics and Advanced Materials*, Vol. 6, No. 2, 2004, pp. 587-592.
- [3] Y. S. Didosyan and H. Hauser, "Magneto-Optical Current Sensor by Domain Wall Motion in Orthoferrites," *Ieee Transactions on Instrument and Measurement*, Vol. 49, No. 1, 2000, pp.14-18. [doi:10.1109/19.836301](https://doi.org/10.1109/19.836301)
- [4] Y. S. Didosyan, H. Hauser and W. Toriser, "Temperature Characteristics of a New Magneto-Optical Current Transformer," *International Journal of Applied Electromagnetics and Mechanics*, Vol. 13, No. 1-4, 2001-2002, pp. 227-283.
- [5] Q. P. Chen, M. Ferraris, *et al.*, "Novel Erbium Doped PbO and B_2O_3 Based Glasses with Broad 1.5 μm Absorption Line Width and Low Refractive Index," *Journal of Non-Crystalline Solids*, Vol. 324, No. 1-2, 2003, pp. 1-11. [doi:10.1016/S0022-3093\(03\)00222-9](https://doi.org/10.1016/S0022-3093(03)00222-9)
- [6] W. N. Li, K. S. Zou, M. Lu, B. Peng, and W. Zhao, "Faraday Glasses with a Large Size and High Performance," *International Journal of Applied Ceramic Technology*, Vol. 7, No. 3, 2010, pp. 369-374. [doi:10.1111/j.1744-7402.2008.02344.x](https://doi.org/10.1111/j.1744-7402.2008.02344.x)
- [7] C. B. Pedroso, E. Munin, A. B. Villaverde, *et al.*, "Magneto-Optical Rotation of Heavy-Metal Oxide Glasses," *Journal of Non-Crystalline Solids*, Vol. 231, No. 1-2, 1998, pp. 134-142. [doi:10.1016/S0022-3093\(98\)00408-6](https://doi.org/10.1016/S0022-3093(98)00408-6)
- [8] A. A. Kharlamov, R. M. Almeida and H. Jong, "Vibrational Spectra and Structure of Heavy Metal Oxide Glasses," *Journal of Non-Crystalline Solids*, Vol. 202, No. 3, 1996, pp. 233- 240. [doi:10.1016/0022-3093\(96\)00192-5](https://doi.org/10.1016/0022-3093(96)00192-5)
- [9] C. Z. Tan and J. Arndt, "Faraday Effect in Silica Glasses," *Journal of Physics B*, Vol. 233, No. 1, 1997, pp. 1-7. [doi:10.1016/S0921-4526\(97\)80001-T](https://doi.org/10.1016/S0921-4526(97)80001-T)
- [10] E. A. Davis and N. F. Mott, "Conduction in Non-Brystalline Systems V. Conductivity, Optical Absorption and Photoconductivity in Amorphous Semiconductors," *Philosophical Magazine*, Vol. 22, No. 179, 1970, pp. 903-922. [doi:10.1080/14786437008221061](https://doi.org/10.1080/14786437008221061)
- [11] Y. Cheng, H. Xiao, *et al.*, "Structure and Crystallization Kinetics of $PbO-B_2O_3$ Glasses," *Ceramics International*, Vol. 33, No. 7, 2007, pp. 1341-1347. [doi:10.1016/j.ceramint.2006.04.025](https://doi.org/10.1016/j.ceramint.2006.04.025)
- [12] M. E. Lines, "Oxide Glasses for Fast Photonic Switching: A Comparative Study," *Journal of Applied Physics*, Vol. 69, No. 10, 1991, pp. 6876-6884. [doi:10.1063/1.347677](https://doi.org/10.1063/1.347677)
- [13] K. Knoblochova, H. Ticha, J. Schwarz and L. Tichy, "Raman Spectra and Optical Properties of Selected $Bi_2O_3-PbO-B_2O_3-GeO_2$ Gasses," *Optical Materials*, Vol. 31, No. 6, 2009, pp. 895-898. [doi:10.1016/j.optmat.2008.10.024](https://doi.org/10.1016/j.optmat.2008.10.024)
- [14] K. Kotkova, H. Ticha and L. Tichy, "Raman Studies and Optical Properties of Some $(PbO)_x(Bi_2O_3)_{0.2}(B_2O_3)_{0.8-x}$ Glasses," *Journal of Raman Spectroscopy*, Vol. 39, No. 9, 2008, pp. 12-19. [doi:10.1002/jrs.1969](https://doi.org/10.1002/jrs.1969)
- [15] Y. Ruan, R. A. Jarvis, *et al.*, "Wavelength Dispersion of Verdet Constants in Chalcogenide Glasses for Magneto-Optical Waveguide Devices," *Optics Communications*, Vol. 252, No. 1-3, 2005, pp. 39-45.

- [doi:10.1016/j.optcom.2005.03.037](https://doi.org/10.1016/j.optcom.2005.03.037)
- [16] C. B. Peroso, E. Munin, *et al.*, “Magneto-Optical Rotation of Heavy-Metal Oxide Glasses,” *Journal of Non-Crystalline Solids*, Vol. 231, No. 1-2, 1998, pp. 134-142.
[doi:10.1016/S0022-3093\(98\)00408-6](https://doi.org/10.1016/S0022-3093(98)00408-6)
- [17] T. Watadabe, K. Muratsubaki, *et al.*, “Hardness and Elastic Properties of Bi₂O₃-based Glasses,” *Journal of Materials Science*, Vol. 36, No. 10, 2001, pp. 2427-2433.
[doi:10.1023/A:1017973830342](https://doi.org/10.1023/A:1017973830342)
- [18] E. Munin, A. B. Villaverde, *et al.*, “Magneto-Optical Rotation of Heavy-Metal Oxide Glasses,” *Journal of Non-Crystalline Solids*, Vol. 231, No. 1-2, 1998, pp. 134-142.
[doi:10.1016/S0022-3093\(98\)00408-6](https://doi.org/10.1016/S0022-3093(98)00408-6)