Magneto-optical properties of metaphosphate and borate glasses

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Abstract. The paper shows results of Faraday Effect study of potassium-alumina-borate and metaphosphate glass under uniform longitudinal magnetic field. The Verde constant of glass under study is obtained based on the experimental data for several wavelengths. Magneto-optical properties of two types of glass: K₂O-Al₂O₃-B₂O₃ glass doped with MnFe₂O₄ nanocrystals and P₂O₅-Tb₂O₃-Ga₂O₃ glass are compared with industrial glass. Application prospects of borate and metaphosphate glass in fields of isolation of laser radiation, current and magnetic field sensing is shown.

1. Introduction
Faraday Effect, which has a number of significant practical applications, is the rotation of the plane of polarization of a light beam passing through a transparent medium in a magnetic field. Magneto-optical materials (crystals, glasses, films) are promising for use in modern high-tech devices such as current sensors [1-3], optical isolators [4-5] in semiconductor devices when measuring the effective mass of charge carriers, for example, in homogeneity degree studies of semiconductor wafers, aimed at rejecting defective samples. The optical isolators greatly benefit from high Verdet constant materials. In these devices the incident plane polarized light is passed through a Faraday rotating material in a magnetic field so as to produce a 45° rotation of the polarization plane. It is then transmitted through polarization analyzer oriented at 45° with respect to the first polarizer. Back reflected light is blocked by this system which is important for sensitive laser systems where back reflected radiation is detrimental to the laser source as well as in fiber laser schemes. The fiber laser systems, which have become very powerful during last decades, also require fiber optical elements including optical isolators. Ferromagnetic and paramagnetic glasses are good candidates for all these applications. Glass with high rare-earth elements concentration (up to 20 mol %) possesses large magneto-optical rotation with high transparency in the visible region [6]. The main restriction of its application is almost linear spectral dependence of the Verdet constant which becomes insignificant in long wavelength region. Use of glass with ferrite particles removes this restriction. The present paper demonstrates the results of the Faraday Effect study in optical active glass medium, comprising of the Verde constant measurements, optical system adjustment, experimentation and physical processes simulation. As a result of the work, an experimental setup was assembled, the influence of the magnetic field on the radiation propagating in the glass was recorded, the angle of rotation of the plane of light polarization was measured, and the Verde constant for samples of synthesized glass was determined.
2. Materials and methods

In the present work two types of glass: the 25 K2O-20 Al2O3-55 B2O3 glass system doped with 3% Fe2O3 and 2% MnO (mol %) and the P2O5-x Tb3O3-(25-x) Ga2O3 (where x varied from 5 to 25) (mol %) glass system were investigated. Both types of glass were synthesized by melt-quenching technique with stirring the melt by the platinum stirrer. Different crucibles were used to synthesis phosphate glass with zero Ga2O3 concentration: silicate (F237) and platinum (F246).

After synthesis the fabricated samples of each composition were cut to several pieces, thereafter borate glass samples were subjected to additional treatments to nucleate manganese ferrite MnFe2O4 nanocrystals (NCs) dispersed in matrix.

Standard experimental setup was used for carrying magneto-optical measurements. Several semiconductor coherent sources of radiation (λ = 405 nm, 532 nm, 632.8 nm, 808 nm, 980 nm) were used. Coil of more than 2 000 turns of copper wire provided 70 T magnetic field.

There were two modes of the experimental setup operation: without current (mode 1) and with current (mode 2). The intensity of light transmitted through two polarizers, according to the Malus law, depended on the relative angle between the transmission axes of the polarizers (α).

\[ I = \frac{1}{2} I_0 \cos^2 \alpha \]  

(1)

This formula was valid when there was no current in the coil (mode 1). In regime 2, the external magnetic field introduced an additional shift in the polarization of the radiation Δα.

\[ I = \frac{1}{2} I_0 \cos^2(\alpha + \Delta \alpha) \]  

(2)

Using the experimental setup I dependence on the relative angle between the polarizer axes in two modes: with the current turned off and with the current turned on – was revealed.

![Figure 1. Schematic diagram of experimental setup. 1 - laser, 2 - lens, 3 - polarizer, 4 - magnetic coil, 5 - analyzer, 6 - collimator, 7 - photodetector](image)

Using the accepted values, two curves were constructed and approximated by function (3) for mode 1 and function (4) for mode 2.

\[ \psi = \text{const} \cdot \cos^2(\alpha + k_1) \]  

(3)

\[ \psi = \text{const} \cdot \cos^2(\alpha + k_2) \]  

(4)

The distance between the curves along the X-axis (the axis of angles) was Δα, i.e. the angle at which the plane of polarization rotated by the magnetic field, Δα was found as the difference between the coefficients k1 and k2. Thereby the value of the Verde constant could be obtained. Generally the Verde constant is measured in rad / (T · m). In this work, a current of 1.5 A was used. Using the mathematical package MathCad, based on the experimental data and equations above, the value of the rotation angle of the plane of polarization was calculated and averaged. The Verde constant was calculated as follows:
\[ V = \frac{\theta}{L} B \]  

where \( L \) – optical path of the light beam inside the glass sample, \( B \) - magnetic field, \( \theta \)- rotation angle.

3. Results

Table 1 and Figure 2 present the results of the Verde constant measurements at various wavelengths for potassium-alumina-borate, metaphosphate glasses and industrial glass “MOS-15”, which is a silicate glass doped with terbium ions. It can be seen that as the terbium concentration increases, the metaphosphate glass Verde constant values approach those for industrial glass. The borate glass with MnFe\(_2\)O\(_4\) nanocrystals has high absorption in the ultraviolet and visible regions being transparent in the near IR therefore the Verde constant at 980 nm is presented only. However the advantage is the big Verde constant value obtained for this type of glass.

In contrast, metaphosphate glasses activated by terbium have high transmittance in the ultraviolet and visible ranges. It is worth noting that in metaphosphate environment terbium ions do not possess luminescence thus not distorting data from detector. This opens the prospect of using these materials in a wide spectral range from ultraviolet to infrared, to create fiber-optic current and magnetic field sensors, as well as Faraday isolators.

Table 1. Mean Verde constant (rad/T m) at various wavelengths for 5%, 10%, 15%, 20%, 25% Tb metaphosphate glass, borate glass with MnFe\(_2\)O\(_4\) NCs (3% Fe\(_2\)O\(_3\) and 2% MnO) and MOS-15 at room temperature.

| Samples          | 5% Tb\(_2\)O\(_3\) F-263 | 10% Tb\(_2\)O\(_3\) F-265) | 15% Tb\(_2\)O\(_3\) F-264 | 20% Tb\(_2\)O\(_3\) F-262 | 25% Tb\(_2\)O\(_3\) F-237 | 25% Tb\(_2\)O\(_3\) F-246 | MOS-15 | 3% Fe\(_2\)O\(_3\) 2% MnO |
|------------------|--------------------------|-----------------------------|--------------------------|--------------------------|--------------------------|--------------------------|---------|-----------------------------|
| Thickness, mm    |                          |                             |                          |                          |                          |                          |         |                             |
| Verde constant at 405 nm | -51.81                   | -113.86                     | -172.11                  | -319.79                  | -324.13                  | -192.92                  | -343.59 | -                            |
| Verde constant at 535 nm | -29.14                   | -68.34                      | -95.69                   | -381.33                  | -162.17                  | -118.43                  | -201.84 | -                            |
| Verde constant at 632.8 nm | -12.95                   | -55.4                       | -67.4                    | -117.3                   | -119.6                   | -37.1                    | -        | -                            |
| Verde constant at 808 nm | -12.3                    | -27.7                       | -40.4                    | -46.9                    | -59.8                    | -43                      | -74.8   | -                            |
| Verde constant at 980 nm | -9.4                     | -24.9                       | -38.4                    | -46                      | -59.8                    | -70                      | -74.2   | +228.57                     |

Table 1.
Figure 2. Spectral dependence of the Verdet constant for different types of terbium doped glass at room temperature (connecting lines are provided for convenience)

4. Conclusions
The Faraday Effect in potassium-alumina-borate doped with iron and manganese ions, and terbium doped metaphosphate glass was studied, and the Verde constant value for these materials was measured. As a result of work, an experimental setup has been assembled; the effect of a longitudinal magnetic field on the radiation propagation in glass was recorded. The experimental data was in good agreement with the approximation curves. Big values of the Verdet constant for the high-terbium metaphosphate glass in blue region and MnFe$_2$O$_4$-doped borate glass in near IR region were obtained. This opens the prospect of using these materials in a wide spectral range from ultraviolet to infrared, to create fiber-optic current and magnetic field sensors, as well as Faraday isolators.

References
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