Magneto-optical properties of terbium-doped metaphosphate and borate glasses

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Abstract. The paper shows the results of Faraday Effect study of borate and metaphosphate glasses doped with various concentrations of terbium under uniform longitudinal magnetic field. The Verdet constant of glass under study is obtained based on the experimental data for several wavelengths. The optical and spectral properties of glasses are also studied.

1. Introduction

Faraday Effect is a rotation of a polarization plane of light due to circular birefringence in a material caused by influence of an external magnetic field. In a non-absorbing or weakly absorbing medium, a linearly polarized monochromatic light beam passing through a material along direction of applied magnetic field experiences circular birefringence, resulting in rotation of polarization plane of incident light [1].

The Faraday Effect has a number of significant practical applications. Magneto-optical materials (crystals, glasses, films) are promising for use in modern high-tech devices, such as current sensors [2] and optical isolators [3].

In the most common magneto-optical materials, terbium ion (Tb³⁺) is used as an ion possessing magnetoactive properties, which creates a large Verdet constant in the visible and near-IR spectral ranges. This was shown in terms of works devoted to both classical magneto-optical crystals TGG [4,5], TSAG [6,7], TAG [8] and terbium-containing magneto-optical glass. In most papers, the authors ultimately conclude that the higher the content of terbium, the better the magneto-optical characteristics in materials transparency window. However, with increasing terbium concentration, the intensity of its absorption bands increases. The main disadvantage of glasses doped with terbium is low transmittance in the wavelength range of < 400 nm and > 1400 nm.

Glass with high concentration of rare-earth elements has a large magneto-optical rotation with high transparency in the visible region [9]. However, the Verdet constant becomes insignificant in the long-wavelength area.

The present paper demonstrates the results of the investigation of optical, spectral and magneto-optical properties of heavily terbium-doped metaphosphate and borate glasses, including absorption spectra registration, refractive index studies, the rotation angle of the light polarization plane measurement and the Verdet constant calculation.
2. Methods and measurements

In the present work three types of glass were synthesized: 75 P₂O₅ – x Tb₂O₃ – (25-x) La₂O₃ glass system (where x varies from 5 to 25 mol %), 50 PbO – 50 B₂O₃ glass system doped with x Tb₂O₃ (x=25, 35 mol %) and 50 PbO – 50 B₂O₃ glass system doped with x TbF₃ (x=25, 35, 45 mol %).

The Verdet constant, which characterizes the magneto-optical properties of a material, cannot be measured directly. Therefore, it was necessary to measure the angle of rotation of the polarization plane of the radiation passing through the glass samples under study. For this purpose, a standard experimental setup was used, the scheme of which is shown in Figure 1.

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

Several coherent sources of radiation were used: He-Ne laser (633 nm), second harmonic of Nd:SSO laser (457 nm), and several semiconductor lasers with 532, 808, and 980 nm wavelengths. The polarizer and analyzer were crossed at an angle of 45 degrees. A magnetic field with an induction of 177 mT was created by a system of 4 magnetic coils, each of them consisted of 2050 turns of copper wire with a diameter of 1.16 mm. Measuring the angles of rotation of the polarization plane, as well as knowing the dimensions of the glass samples, allowed us to calculate the Verdet constant for each sample using the formula obtained from formula (1):

\[ V = \frac{\theta}{H \cdot l} \]  

where \( l \) is the sample length (m), \( H \) is the magnetic field strength (T), \( \theta \) is the angle of rotation of the polarization plane (deg).

Optical density spectra were recorded using a spectrophotometer Lambda 900. The measurements were carried out in the wavelength range of 250 - 3000 nm (Figures 4, 5). The obtained spectra of optical density were converted into the absorption coefficient by the formula:

\[ \alpha = \frac{D}{l} \]  

where \( \alpha \) is the absorption coefficient, \( D \) is the optical density, and \( l \) is the sample thickness.

The refractive index was measured on an Abbe IRF-454 refractometer for a wavelength of 589.3 nm with an accuracy of \( \pm 0.0005 \). The results of the measurements are shown in Tables 1 and 2.

3. Results

Figures 2 and 3 present the results of the Verdet constant measurements at various wavelengths for metaphosphate and borate glasses doped with various concentrations of terbium. It can be seen from the graphs obtained, the Verdet constant increases with increasing concentration of terbium ions and decreasing incident radiation wavelength. Its values become insignificant in the long-wavelength region.
Figure 2. Verdet constant spectral dependence of metaphosphate glasses with different concentration of terbium-comprising dopants (mol%).

Figure 3. Verdet constant spectral dependence of borate glasses with different concentration of terbium-comprising dopants (mol%).

The results of the absorption spectra measurements are shown in Figures 4 and 5.
According to the literature [10], the set of the absorption bands of terbium ions is located in the wavelength region of 350–500 nm. For this reason, materials doped with terbium acquire a yellow tint. However, in our case these bands had a low intensity; therefore, the materials under study were colorless. The absorption spectra show the presence of two broad absorption bands in the region of 1500–2500 nm, which are associated with Tb$^{3+}$ ions. With terbium concentration increase in the glass composition, the intensity of these bands increased.
Table 1. The refractive index of the metaphosphate glasses with different Tb$_2$O$_3$ concentration (mol %).

| Samples       | 5% Tb$_2$O$_3$ | 10% Tb$_2$O$_3$ | 15% Tb$_2$O$_3$ | 20% Tb$_2$O$_3$ | 25% Tb$_2$O$_3$ |
|---------------|----------------|------------------|------------------|-----------------|-----------------|
| Refractive index | 1.5891         | 1.5831           | 1.5756           | 1.5723          | 1.5599          |

Table 2. The refractive index of the borate glasses under study.

| Samples       | 25% Tb$_2$O$_3$ | 35% Tb$_2$O$_3$ | 25% TbF$_3$ | 35% TbF$_3$ | 45% TbF$_3$ |
|---------------|-----------------|-----------------|-------------|-------------|-------------|
| Refractive index | 1.6572         | 1.6574           | 1.6570       | 1.6571       | 1.6572       |

The refractive index of phosphate glasses decreases with an increase in the concentration of terbium, while in borate glasses we observe an inverse dependence.

4. Conclusion
In this work, phosphate and borate glasses with different concentrations of terbium ions were synthesized. The absorption spectra of glasses in the visible and near-IR spectral regions were obtained. All glasses have high transparency in the wavelength range from 300 to 1500 nm. The refractive index of phosphate glasses decreases, while in borate glasses it increases insignificantly with increasing terbium concentration. Measurements of the rotation angle of the light polarization plane and the subsequent calculation of Verdet constant showed that, with increasing registration wavelength, the value of Verdet constant decreases for all the glasses under study. Concentration studies of the magneto-optical characteristics showed a direct relationship between the content of the paramagnetic ions and the value of Verdet constant for all glasses doped with terbium ions.

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