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Investigation of $Gd_3Ga_5O_{12}$ by Micropolarimetry*

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ABSTRACT

This paper summarizes the results of investigation of garnets $Gd_3Ga_5O_{12}$ (GGG) on the basis of their optical activity. Dispersion of Verdet constant was measured in the visible light range and in a strong magnetic field. The applied technique, namely micropolarimetry, exhibits high resolution which corresponds to the type of polarization microscope used in the investigation.

Keywords: Optical Activity; Verdet Constant; Paramagnetic Garnet; Polarization Microscopy

1. Introduction

Paramagnetic garnets $X_3Ga_5O_{12}$ (X = rare earth) represent interesting materials for basic research as well as for numerous applications. Considerable attention was paid to garnet GGG which had been used as a substrate for bubble memory chips [1]. The bubble memory was deemed to be potentially able to reduce fast mechanical rotation which is typical for the case of a classical hard disc. Somewhat later the optical activity of these garnets, induced by a magnetic field, was studied in a greater detail. The origin of this type of activity is based on the action of classical Lorentz force on the electronic structure of these materials. As a result, the splitting and shifts of their spectral lines are observed [2].

Optical activity is, in general, represented by rotation of the plane of linearly polarized optical radiation during its passage through a material. Commercial polarimeters (saccharimeters) are standard techniques for determination of specific rotation in solutions. With solid materials, special laboratory equipment is usually used. Low absorption in the required frequency range and high value of specific rotation are two main parameters to consider in various applications. The magnitude of magneto-optical activity, in the case of paramagnetic and diamagnetic materials, is characterized by Verdet constant V.

Several types of garnets have been experimentally investigated. The value of Verdet constant $V = 11.8\,\text{rad/Tm}$ at room temperature and at $\lambda = 633$ nm [3] was found for garnet SGG $(S = Sm)$. Under the same conditions, one order of magnitude higher value of $V = 134$ rad/Tm was found for crystal TGG $(T = Tb)$ [4].

The highest value of Verdet constant was found for NGG $(N = Nd)$, namely $V = 3490\,\text{rad/Tm}$ at $\lambda = 490$ nm [5]. In this case the Faraday rotation was measured as a function of the magnetic induction and the extrapolation to zero magnetic induction of thus obtained dependence was used to obtain the value of Verdet constant. The measurements were carried out at the temperature of 4.2 K and at the wavelength range of 440 nm to 850 nm.

This paper describes the results of experimental investigation of monocrystalline samples of GGG using a micropolarimetric apparatus. The main advantage of the proposed procedure is the ability to study magneto-optical activity of solids with high lateral resolution.

2. Experimental

A monocrystalline sample GGG in the form of a rectangular parallelepiped, with the base of 4 × 5 mm, polished to the optical quality, was prepared for these experiments. The height of the parallelepiped along the crystalline direction (111) was 10.5 mm. The height was therefore almost maximum, taking into account the working space of a standard microscope. The colourless crystal GGG belongs to a cubic crystallographic system with space group Ia3d. From the optical point of view, it is an isotropic material, therefore optically inactive.

The experimental equipment consists of a commercial polarization microscope Leica DM 2500P equipped with a magnetizing device, CDD camera COHU 4910 and measuring software NIS-Elements 2.3. Schematic diagram of the experimental arrangement is shown in **Figure 1**. The microscope employed classical halogen lighting the spectrum of which could have been changed using

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*Highlights: Dispersion of the Verdet constant for a garnet $Gd_3Ga_5O_{12}$ was investigated in the visible light range and in a strong field of permanent magnet.

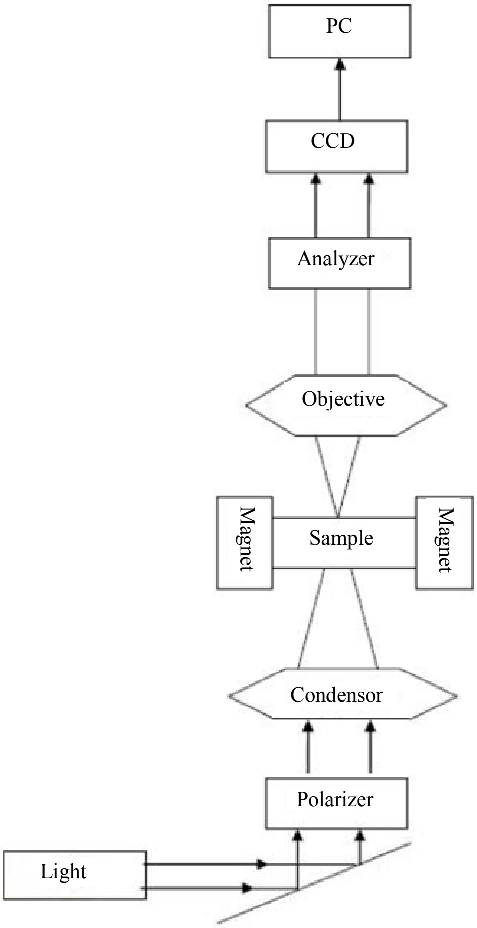

Figure 1. Schematic diagram of apparatus.

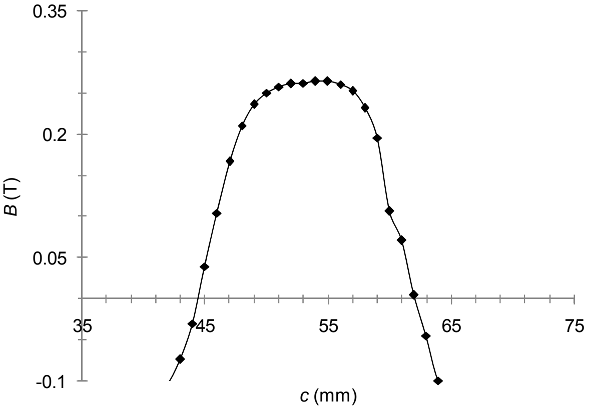

Figure 2. Magnetic induction *B* (component in the direction of the light beam) versus position *c* on the axis of the gap of the permanent magnet.

Table 1. The colour filters using in this study and their effective wavelengths.

Colour filter	λ_{eff} [nm]
Red	612
Yellow	575
Green	536
Blue	464

colour filters. The effective wavelengths of these filters were acquired using the measurements of optical activity of monocrystalline quartz and are shown in **Table 1**.

When a material is under the influence of magnetic induction *B*, the magneto-optical activity will develop an angle of rotation of the plane of polarization *α* which can be expressed as

$$\alpha = V \cdot B \cdot t .$$

In this expression, *V* is the Verdet constant, *B* is the component of magnetic induction in the direction of light propagation and *t* is the thickness of the material through which the optical radiation is passing [2]. Sufficiently strong magnetic field was generated by a ring-shaped permanent magnet NdFeB. The magnet was magnetized along the axis of the ring gap. The pattern of the magnetic induction *B* along the magnet axis, as obtained experimentally, is shown in **Figure 2**. The mean value of the magnetic induction acquired from this dependence is

$$B_{\text{mean}} = 0.211\text{T} .$$

Our experiments were carried out in the transmitting mode. Position of the crystal was chosen in such a way so that the field of view was divided approximately into two parts. The crystal was placed in the first part of the field of view, in which the light beam passed through the entire height of the parallelepiped. In the other half of the view field the light passed only through the optical system which was under the influence of the stray magnetic field. At least one measuring probe was placed in each part of the field of view. Using the CCD camera, the probe detected the intensity *I* of light that had passed. This intensity depends on angle *φ* between the polarizer and the analyser.

If the light passes through the optical system without the sample, then the minimum value of the intensity of light (crossed polarizers) takes place for two angles, namely for $\varphi_{m1} = 90^\circ$ and for $\varphi_{m2} = 270^\circ$. These angles define the "zero", or the "background" of the optical set-up. For a probe placed on the sample two additional minimum values are obtained and the angle of rotation *α* is given by the difference between the corresponding angles *φ*. This difference is either positive or negative depending on whether the measured material is right-handed or left-handed. In order to determine the direction of rotation the right-handed wafer of SiO_2 is used as a standard.

Electronic noise significantly affects the local measurement of the intensity of light. In order to reduce the noise, the signal in each probe was taken and registered one-hundred times every 300 milliseconds. Subsequently the angle φ was changed in constant steps. In order to obtain the approximate values of the minima, the step of 5° was chosen and the measurements were taken for the entire angle of 360°. In order to improve the accuracy of the positions of the minima, the step of either 1° was selected. This regime proved to be satisfactory even from the point of view of mutual time stability of the optical system and the software.

3. Results

While analysing the results, it was necessary to eliminate the first twenty values from each set of hundred values, for each position of the analyser, *i.e.* the values obtained during the movement of the analyser. The mean value was then taken from the subsequent 80 values. A typical pattern of the orientation dependence of the transmitted "red" light on angle φ is shown in **Figure 3**.

It is apparent that the minimum occurs in the close vicinity of 90°. In order to obtain a more accurate value, the interval of 80° to 105°, in steps of 1° was investigated. The detailed pattern is shown as an inset in **Figure 3**. The minimum value was determined by the least-square method for a polynomial of the second order, using five experimental points. In a similar manner, angles of rotational for the other colour filters were found. The summary of the measurements, expressed as reciprocal values of Verdet constant, V^{-1} versus λ^2, is given in **Figure 4**.

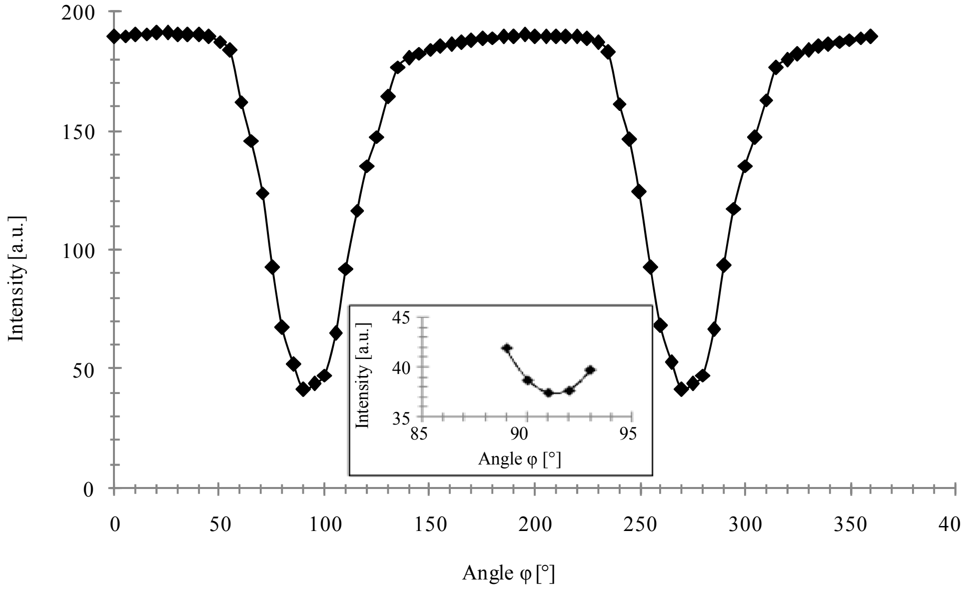

Figure 3. Typical dependence of intensity *I* of the "red" light on the angle φ between the polarizer and analyser. The inset displays the details of the dependence.

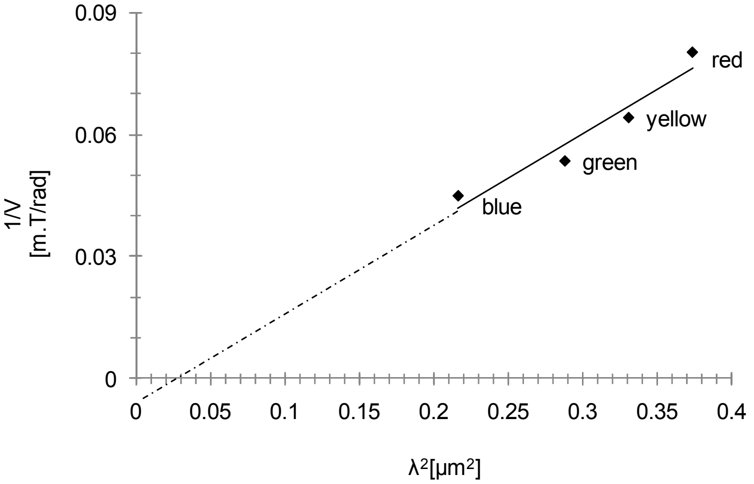

Figure 4. Dependence of the inverse value of Verdet constant V^{-1} on λ^2 for the crystal GGG.

4. Discussion

The pattern of dispersion of Verdet constant, shown in **Figure 4**, indicates that the proposed and realised technique offers, for the GGG crystal, acceptable and, at the same time, expected results. Monocrystal GGG can be, in the visible region, characterised by the approximately linear dependence of the inverse value of Verdet constant on λ^2, namely

$$V^{-1} = \text{const} \cdot \left(\lambda_0^2 - \lambda^2\right).$$

This relationship corresponds to a dispersion curve describing "classical" optical activity. Linear extrapolation to the zero value yields, for the measured crystal GGG, the wavelength of λ_0 = 153 nm, where strong absorption of the UV radiation can be expected.

5. Conclusion

This report presents the results of investigation into micropolarimetry which allows to measure locally optical rotation of solids as wells as solutions, even in a magnetic field. The magnitude of Verdet constant was determined for crystal GGG. The value of the constant, in the visible region, ranges from 12.5 to 22.3 rad/Tm.

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