Temperature dependence of the Faraday rotation of terbium gallium garnet ceramic

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INTRODUCTION

The most popular, principal technique in high power lasers is the linear polarization rotation by Faraday Elements (FEs) for laser output extraction out of the system, isolation of laser chains, and birefringence compensation in solid-state laser medium [1]. Recent studies have indicated that under high average power, even solid-state FEs suffer from their own thermal effects seriously due to small absorption coefficient α (for example, α of Terbium Gallium Garnet (TGG): Tb3Ga5O12 is the order of 10-3cm-1 at 1- μ m wavelength). Especially, the absorption of laser radiation induced nonuniform temperature distribution over the cross-section of a medium leads to thermal birefringence, which causes the depolarization in FEs [2]. Subsequently several techniques have been proposed for the compensation for birefringence of FEs. One method bases on the idea of subtracting the phase incursion by using two FEs and reciprocal optical element [3]. Another method is to divide the Faraday medium into multi-disks similar to solid-state disk lasers [4,5].

Cryogenic cooling of Faraday materials has a possibility for decreasing thermal birefringence, because the dramatically increasing Verdet constant in addition to increasing thermal conductivity and suppressing the thermal expansion can be expected at cryogenic temperature. It may expect that the length of the Faraday medium could be shorter and hence absorbed power and thermal birefringence in Faraday medium would decrease. The effectiveness of cryogenic technique is demonstrated by improvement of the laser efficiency and the beam quality of solid-state lasers [6-8]. And the recent study indicated that this technique is applicable for FEs at liquid nitrogen temperature [9]. Verdet constant of paramagnetic material is inversely proportional to temperature. Therefore it is expected that the suppression of the thermal birefringence is more effective under the liquid nitrogen temperature. Temperature dependence of Verdet constant of single crystalline TGG that is the most popular material for FEs is measured from 266K to 353K [10]. However, it is necessary to measure Verdet constant under liquid nitrogen temperature for designing the FEs by cryogenic scheme.

In this study we report the temperature dependence of Verdet constant of single crystal TGG from 9.1 K to 300K and new material of TGG ceramic from 7.8 K to 300 K at 1053 nm of wavelength. Verdet constant of the TGG ceramic is a difference only of 0.8 % compared with the value of single crystal. The measured value of Verdet constant for TGG ceramic at 7.8 K is 40 times higher than that at 300 K. It is expected that a TGG ceramic that can be enlarged in the future have similar thermal property of TGG. So this material is one of the promising materials for high peak and high average power lasers instead of Tb doped glass material which have low thermal conductivity and high absorption coefficient compared with a TGG.

EXPERIMENTAL SETUP

In Fig. 1 the experimental setup is schematically depicted. Measured samples are single crystalline TGG with [111] orientation grown by melt method (12.75 mm in length and 4.7 mm in diameter) and TGG ceramic (5.95 mm in length and 5 mm x 1 mm cross section) made by Konoshima Chemical Co., Ltd. Samples were set into the vacuum chamber of cryostat (Iwatani HE05) and were thermally contacted by copper holder with cryostat. A 1053nm diode-pumped Nd:YLF continuous wave 500mW laser (IRCL-100-1053, CrystaLaser) were used as optical sources. The sample temperature was controlled by a cryostat and the sample temperature is measured by calibrated Kp-Au thermo couple. A pulsed uniform magnetic field up to 253 G with pulse duration of 100 ms was applied to the sample along its axial direction by Helmholtz coil that was set at outside of the vacuum chamber. Two Gran prisms were used in this experiment and second Gran prism was rotated by a stepping motor. The laser light was delivered to a sample in the vacuum cryostat through the first Gran prism and the entrance window. When electric current produced magnetic field, the polarization of light is rotated by the Faraday effect and modulated by the second Gran prism. The light intensity is measured by a silicon photo detector. Polarization plane is rotated by the Faraday effect and the transmitted light intensity I are related by Malus's law as

$$I = I_0 \cos^2(\theta + \theta_0) \qquad (1)$$

Here I0 is incident light intensity at parallel axes of the two prism, θ 0 is the initial bias angle between the transmission axis of the two prisms, and θ is a rotation angle due to the Faraday effect.

Before electric current produced magnetic field by Helmholtz coil, sample was inserted between Gran prism and the second prism were rotated to minimum I. This angle of second prism is the origin of rotation angle $\theta 0 = 0°$. An angle of minimum I is changed by Faraday effect. At this time, when the second prism is rotated to minimize I, $\theta 0$ is obtained and an angle of Faraday rotation is obtained by Eq. (1). The rotation angle is determined by data fitting to Eq. (1). Fitted data is over 50 points which is angle of vicinity of the angle of the minimum I. In consequence the accuracy of rotation angle of this system was estimated to better than 0.002°. A measured θ and Verdet constant V are related by the familiar expression as

$$\theta = VHL \qquad (2)$$

Here H is magnetic field and L is length of a sample. Magnetic field H is measured by Gauss meter (MODEL5080, F.W Bell), which is proportional to electric current of Helmholtz coil. So Verdet constant V of samples are derived from Eq.(2).

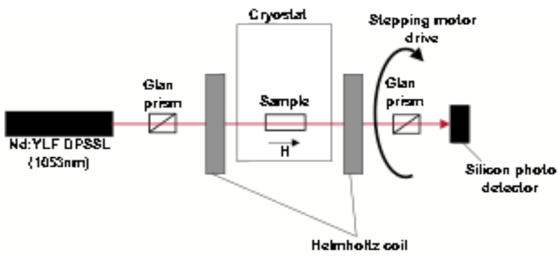

Fig. 1. A schematic diagram of experimental setup for the measurement.

RESULTS AND DISCUSSION

In Fig.2 the measured Verdet constant V of single crystal and TGG ceramic is shown as a function of cooling temperature, expressing its inverse-temperature. The extinction ratio is maintained better than 1:5000 at each measurement. At room temperature of 300 K, measured V value of single crystalline TGG is 36.4 rad/T·m that agrees with published values (35-40 rad/Tm) for the Verdet constant in this material [11-13]. The V value of single crystalline TGG is inversely proportional to temperature and it is noted that Verdet constant at 9.1 K is 31 times larger than that at 300 K. At 300 K the V value of TGG ceramic is 36.2 rad/T·m. It is good agreement within 0.8 % of the value for single crystal. Verdet constant at 7.8 K is 1453 rad/T·m. It is 40 times larger than that at 300 K and inversely proportional to temperature too. The slope of the straight line is 13296 rad·K/m·T. From this fitting line Verdet constant at 4.2 K is extrapolate to a large 3165 rad/T·m. Therefore a length of single crystal and poly crystal TGG for use of FEs can be decreased to 1/87.4 in same magnetic field. This result is very effective for reducing the thermal birefringence in FEs for high average power lasers.

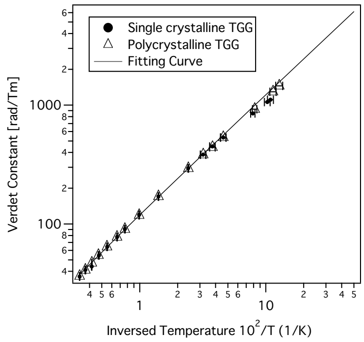

Fig. 2. The temperature dependence of Verdet constant of single crystal and TGG ceramic.

CONCLUSION

Measurements of the Verdet constant have been carried out in the paramagnetic single crystalline and polycrystalline terbium gallium garnet. This work is showed that recognition of the extremely high (87.4 times larger than that at room temperature) Verdet constants can be used at liquid helium temperature. It may be expected that the length of the Faraday medium could be shorter and hence absorbed power and thermal birefringence in Faraday medium would dramatically decrease. In addition, from our measurement Verdet constant of TGG ceramic is almost same as the single crystal. From this work TGG ceramic is feasible material for Faraday element for extreme high peak and high average power lasers like laser-fusion driver in future.

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