Development of cryogenic TGG ceramic based Faraday rotator for inertial fusion driver

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Abstract. As the first demonstration of Faraday effect with a TGG ceramics, the Verdet constant was experimentally evaluated to be 36.4 rad/Tm at 1053 nm, which is same as that of the single crystal. The Verdet constant was improved for 87 times greater than that at room temperature. We have confirmed the feasibility of Faraday material for IFE driver by use of cryogenic TGG ceramics.

1. Introduction

Recently, pulse lasers with both of high pulse energy and high average power, are strongly desired for various industrial and scientific applications such as laser peening, laser processing, high-energy particle generation, hard x-ray generation, inertial fusion energy (IFE) and so on [1]. A Faraday element is one of the indispensable key optics for isolation of laser chains and birefringence compensation of laser materials in such high-power laser systems. There are three critical factors of high Verdet constant, high thermal strength and size scalability for the Faraday elements. Terbium-doped materials are the most popular due to a high Verdet constant. A terbium-doped glass has been often used for high pulse energy lasers due to its superior size scalability. Its low thermal characteristics (thermal conductivity of Tb: doped glass FR-5 is 0.84 W/mK), however, is not preferred for repeatable operation. On the other hand, a Faraday crystal shows excellent thermal conductivity to be suitable for high average power operation, but it is difficult to obtain a large aperture crystal.

As one of solutions for the realization, a terbium gallium garnet (TGG) ceramics will be the promising Faraday element due to a high Verdet constant of 36-40 rad/Tm, high thermal conductivity
of 7.4 W/mK, and excellent size scalability. The TGG ceramics have been reported in 2003 for the first time. Then the theoretical analysis of thermal birefringence in TGG ceramics has been reported. However, no Faraday effect measurement with TGG ceramics has been demonstrated because of its low optical quality. The recent ceramics technology enables to produce laser-graded TGG ceramics. The size is still small now and the large aperture ceramics will be obtainable in future.

In an extremely high pulse energy laser system such as IFE lasers, there is another problem of a strong magnetic field, which is difficult to be isolated. The strong magnetic field often interferes with electronic control systems and diagnostic devices. Also, a huge magnet system is necessary. In fact, a huge superconductive solenoid has been used in fusion lasers. Improving a Verdet constant, the required magnetic field strength will reduce and, the whole magnetic system size will become compact. Cryogenic cooling of materials often becomes an easy and effective method to control various material coefficients. Recently, cryogenic cooling of several active elements concerning to solid-state lasers has been demonstrated to improve thermal characteristics and to tune a stimulated emission cross section. Using TGG crystal, some groups have been estimated the Verdet constant between 77K and 300K by measuring the rotation angle at a constant magnetic field. At 77K, Faraday rotation angle was 3.5 times of that at 293K.

In this paper, we have measured the temperature dependence of Verdet constant and thermal conductivity of laser-graded TGG ceramics at 1053 nm wavelength. Also, a TGG single crystal was used for comparison. The Verdet constant difference between the ceramics and the crystal is only 0.8%. The Verdet constant of TGG ceramics increases at 1453 rad/Tm at 7.8K, which is over 40 times higher than that at 300K. The measured thermal conductivity was corresponding to TGG single crystal between 100 K and room temperature. This will be one of the promising Faraday materials for high-power lasers for inertial fusion energy.

2. Experimental setup

2.1. Verdet constant

A experimental procedure for the Verdet constant measurements of TGG ceramics is as follows. The laser light goes through a sample, which is between a pair of Glan laser prisms used for analyzer and polarizer respectively. The transmitted laser intensity is measured by a silicon photo diode. A polarization plane of laser light is rotated by Faraday effect owing to a magnetic field. The transmitted laser intensity I is expressed by Malus’s law. A diode-pumped Nd:YLF continuous wave laser (IRCL-100-1053, CrystalLaser) were used as optical sources. The wavelength and output power are 1053 nm and 500 mW at maximum respectively. The extinction ratio of the prism is 0.2 x 105. The analyzer prism is attached to a stepping motor driven rotation stage, which surface plane is perpendicular to the optical axis. A TGG ceramic (Konoshima Chemical Co., Ltd., 5.95 mm in length and 5 mm x 1 mm cross section) and a TGG single crystal (OFR, Inc) with <111> orientation (12.75 mm in length and 4.7 mm in diameter) are used as Faraday materials. Each of them is cramped by a copper holder. A thin indium foil is used between the material and the holder to improve the thermal contact. The holder is attached to a temperature-controllable cryostat (Iwatani HE05) and set in the vacuum chamber. The temperature is measured by a calibrated Kp-Au thermo couple on the material surface. The controllable temperature range is between 7.8±2.1K and 300±0.1K. A spatially uniform magnetic field is applied to the material by using double Helmholtz coils. The applied magnetic field is temporally pulsed with duration of 100 ms because of suppression of the coil heating. The magnitude of the magnetic field is 253 G at maximum. The magnetic field strength, which is calibrated with a Gauss meter (MODEL5080, F.W. Bell), is controlled by an electric current of the Helmholtz coils. The laser intensity I is measured at uniform time-region of top-hat temporal magnetic field, then fluctuation of the detected intensity I was 0.8% RMS. The extinction ratio of the transmitted laser intensity is maintained better than 1:5000 during measurements. In consequence the accuracy of the rotation angle of this system was estimated to better than 17.44 mrad.
2.2. Thermal conductivity

Thermal conductivity of TGG ceramics has been measured by the Steady-state longitudinal heat flow method. The sample size of TGG ceramics is 5.95 mm in length and 5 mm x 1 mm cross section. It is made by Konoshima Chemical Co., Ltd. A face of TGG ceramics is thermally contacted with the cooling head of the cryostat. We attached the heater at the other side of TGG ceramics. Two different points of temperature of TGG ceramics were measured by thermocouples. We have used the equation of \( \kappa = QS/\Delta TL \) for determining thermal conductivity. \( Lt \) (m) is the distance between thermocouples. \( Q \) (W) is the heating power of the heater. \( S \) (m\(^2\)) is the cross section of TGG ceramics. \( \Delta T \) (K) is the temperature difference between the thermocouples.

3. Result and discussion

At room temperature of 300K, the measured Verdet constant of TGG single crystal is 36.2 rad/Tm. That agreed with published values (35-40 rad/Tm) [2,3]. The Verdet constant of TGG ceramics is 36.4 rad/Tm at 300K is almost same as that of single crystal, and the tiny difference is within the measurement error. The TGG ceramic is composed of TGG single crystal grains and boundary layers. The boundary layer occupation in volume is below 0.003. If the large-size ceramics are obtainable, a higher pulse energy operation will be realized.

The measured Verdet constants \( V \) of the TGG single crystal and TGG ceramic are plotted in Fig. 1 as a function of the absolute temperature. The Verdet constant of the ceramic at 7.8K is 1453 rad/Tm, which is 40 times larger than that at 300K, in addition, 1122 rad/Tm for the single crystal at 9.1K. Within this temperature range, the experimental data are inversely proportional to the absolute temperature. In consequence, Verdet constant at 4.2K is extrapolated at 3164 rad/Tm. The required magnetic field is, therefore, reduced to 1/87, resulting in stable electric control of the laser system, the accurate diagnostics and the reduced magnetic system size. In addition, the length of the Faraday material can be shortened to 1/87 in the same magnetic field, which gives advantages for short pulse lasers in femto-seconds due to a lower spectral dispersion.

Our measured thermal conductivity of the ceramics which is shown in Fig. 2 is 4.94±0.25 W/mK that agrees with published values (4.5W/mK-7.4W/mK) [2,4]. And the temperature behaviors of the thermal conductivity for both the single crystals and the ceramics are closely similar at about 100K. From 100K to 50K, the influence of the Umklapp scattering decreases, and the thermal conductivity is limited by the grain boundary scattering in the ceramics. Compared with terbium-doped glass materials at room temperature, the magnitude is about one order higher between 100K and 300K, which is preferable for high average power operation.

![Fig. 1. The temperature dependence of Verdet constant of TGG single crystal and TGG ceramics.](image-url)
Fig. 2. The temperature dependence of thermal conductivity of TGG single crystal [4] and TGG ceramics.

4. Conclusion
The temperature dependence of Verdet constant and thermal conductivity of the paramagnetic TGG ceramics has been measured for the first time to our knowledge. The temperature dependence of its magnitude is almost same as that of a single crystal. If the large-size ceramics are obtainable, a higher pulse energy operation will realize. At low temperature, the Verdet constant increases, for example, to 87 times magnitude at liquid helium temperature compared with that at room temperature. The required magnetic field reduces, resulting in the stable electric control system without electromagnetic interference, the accurate diagnostics and the reduced magnetic system size. Also, the shortened Faraday material may be used in femto-second lasers due to lower spectral dispersion and high average power laser due to sapphire sandwiched thin disk faraday medium [5]. In addition to these improvements, the observed thermal conductivity of ceramics is one order higher than glass materials. Using cryogenic cooled TGG ceramics, new laser systems with both of high pulse energy and high average power such like fusion reactor driver would be realized.

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