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Viewpoint article

Promising magneto-optical ceramics for high power Faraday isolators

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ABSTRACT

Magneto-optical ceramics with excellent optical quality, large size and high Verdet constant can be used in high powder Faraday isolators of the next-generation. In this viewpoint, fabrication, microstructure, properties and applications of some promising magneto-optical ceramics, namely polycrystalline garnet and sesquioxide based materials, are mainly demonstrated. And we also propose the composition design, performance optimization and function expansion of the transparent magneto-optical ceramics.

1. Introduction

High-energy and high-average-power lasers have been widely used in various scientific and industrial applications including inertial fusion energy [1], extreme ultra-violet generation [2], laser processing [3] and so on. Faraday isolators are essential optical devices in such high-power laser systems which are used for optical isolation, polarization control, and birefringent compensation [4–6]. As the key components of Faraday isolators, magneto-optical materials must have a few critical factors: a high Verdet constant, excellent optical quality, size scalability, a high thermal strength and high laser-induced-damage threshold [7–10]. Commonly used magneto-optical materials include glasses, crystals and ceramics. Tb-doped silicate and phosphate glass have been often used for high pulse energy lasers due to its superior size scalability [11–13]. However, this amorphous glass material is not preferred for repeatable operation due to its low thermal conductivity. On the other hand, magneto-optical crystals, such as terbium gallium garnet (TGG) and terbium aluminum garnet (TAG) single crystals, possess high thermal conductivity which are suitable for high average power operation. However, single crystals take significant time to grow, and their growth technology makes it difficult to obtain a large aperture crystal—which is required to prevent laser-induced damage or the nonlinear optical effects of the magneto-optical medium during high-intensity laser operation [14]. Therefore, making application of magneto-optical crystals in high-energy lasers is also problematic.

One solution to this problem is developing high power Faraday isolators based on magneto-optical ceramics, since they have excellent size scalability while maintaining high thermal conductivity and Verdet constant. In addition, current optical ceramic technology permits fabricating magneto-optical ceramics with high optical quality comparable to single crystals. Still more important is that the ceramic technology provides an alternative way to prepare incongruent magneto-optical materials which cannot be grown by conventional crystal growth technology, such as TAG [15–17]. Up to now, magneto-optical ceramics can be classified into garnet structure based ceramics and sesquioxide based ceramics. TGG and TAG transparent ceramics are typical garnet based magneto-optical ceramics which are applied in the visible and near-infrared spectral regions. It has been shown already that the basic physical properties of TGG and TAG ceramics are comparable to and even better than that of the corresponding single crystals, and thus they have been considered as promising candidates for high power Faraday isolators [18–21]. The reported sesquioxide based magneto-optical ceramics include terbium oxide (Tb_2O_3), holmium oxide (Ho_2O_3), dysprosium oxide (Dy_2O_3), etc. Among them, Tb_2O_3 ceramic shows the largest Verdet constant, which is 3.8 times than the TGG single crystal. Therefore, it is possible to minimize the magneto-optical element length and the magnet to build an optical isolator. The high Verdet constant of Tb_2O_3 ceramic makes it very promising for Faraday devices.

In this viewpoint, we review the fabrication process, all-sides properties and recent progress of garnet based and sesquioxide based magneto-optical ceramics. Based on the recent experimental results, we also point out the existing problems and forecast the future development and exciting possible applications of these transparent magneto-optical ceramics.

2. Garnet based magneto-optical ceramics

The first TGG ceramic sample was fabricated by Dr. Ikesue, and the possibility of its use in a high-power Faraday isolator was reported in

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2003 [22]. In 2004, Kagan and Khazanov reported the theoretical analysis of thermal birefringence in TGG ceramics [23], however, Faraday effect measurement of TGG ceramic was not demonstrated due to its low optical quality. With the development of ceramic processing technology, the optical quality of TGG ceramics has been gradually improved. The Faraday effect of TGG ceramics was first observed by Yasuhara et al. in 2007 [11]. They measured the temperature dependence of Verdet constant of TGG ceramics at 1053 nm and compared it with TGG single crystal, as shown in Fig. 1(a). The Verdet constants of the TGG ceramics and single crystals are nearly the same and the difference is only 0.8%. For TGG ceramics, the Verdet constant at liquid helium temperature is 87 times larger than that at room temperature. In 2011, Yoshida et al. systematically investigated the optical properties (optical scattering properties and laser induced bulk damage threshold), Faraday effect and Verdet constant of TGG ceramic, which was provided by Konoshima Chemical Co. Ltd. [7]. The ceramic sample was fabricated by slip casting combined with the vacuum sintering method and it shows a uniform grain size distribution ranging from 0.3–3 μm. Transmission curves of 10 mm thick TGG single crystal and ceramic samples are presented in Fig. 1(b). The spectra are almost equivalent above 600 nm while the transmittance of the ceramic sample is slightly lower than that of the single crystals in the <600 nm range. The optical scattering of the TGG ceramic (5×10^{-4}/cm) is similar to the TGG single crystal at 1064 nm. The optical damage threshold at 1064 nm for the TGG ceramic is 5.1 ± 0.5 J/cm^2, which is comparable to the TGG single crystal. The Verdet constant of the TGG ceramic at 1064 nm is 36–40 rad/(T·m) at room temperature, and is almost the same as that of the single crystal. The maximum extinction ratio of the Faraday effect is in excess of 35 dB for the TGG ceramic. These results show that TGG ceramic is a promising Faraday material for high-average-power lasers.

The optical performance of Faraday isolators will be degraded under high-average-power operation due to the thermal effects, such as thermal birefringence and thermal lens effects. Yasuhara et al. experimentally evaluated the thermally induced depolarization and thermal lens effect of a 45° TGG-ceramic-based Faraday isolators at a high-average-laser power [6]. Fig. 2(a) shows the experimental results of integral depolarization γ in TGG ceramic samples with or without a magnetic field. The maximum value of γ with 45° Faraday rotation in a magnetic field is 5.48×10^{-4} at laser power $P = 257$ W, which suggests that this TGG-ceramic-based Faraday isolator maintains an isolation ratio of 33 dB at a laser radiation power of 257 W. The laser power dependence of the integral depolarization of TGG ceramics is nearly the same as the calculation result for a TGG single crystal with a ⟨111⟩ crystal orientation. The thermal lens power in the Faraday isolators constructed on the basis of a 9.15-mm-long TGG ceramic rod was also evaluated. A focal length of 9.5 m is obtained at a laser power of 257 W, and the estimated focal lengths at 340 and 600 W are 7.2 and 4 m, respectively. These values can be corrected by combining the thermal lens with a spherical lens. This result is acceptable for the Faraday isolators during laser operations at the 600 W level. The temporal stability of the Faraday rotation angle and the depolarization were measured at a laser power of 257 W, as shown in Fig. 2(b). It can be seen that the rotation angle converges to around 45.5° after 2 min while the integral depolarization is stable within the experimental time range. This result indicates that temperature stabilization of the TGG ceramic rod is effective in removing heat from the rod. All these experimental results show that a Faraday isolator based on a thermally stabilized TGG ceramic is suitable for high-average-power laser operation.

TAG transparent ceramic is considered to be one of the candidate materials for the next-generation Faraday isolators since it has a higher Verdet constant than TGG [24–26]. In 2011, Lin et al. firstly reported the TAG transparent ceramics which were fabricated by the solid-state reaction method [27]. The in-line transmittance of the sample reached about 75% in the 400–1600 nm region, the Verdet constant was measured to be −172.72 rad/(T·m) at 632.8 nm and the thermal conductivity was approximately 6.5 W·m^{-1}·K^{-1} at room temperature. Chen et al. optimized the dosage of MgO for the sintering of TAG transparent ceramics [28]. The optimal amount of MgO was 0.1 wt% and the optical transmittance of the corresponding sample was improved to above 80% in the 550–1500 nm region. Besides the solid-state reaction method, vacuum sintering of powders synthesized by wet-chemical approaches is also an effective way to fabricate TAG transparent ceramics. Wet-chemical synthesis of multi-cation oxides for ceramics fabrication has many advantages such as atomic level mixing of the starting material, low synthesis temperature, and excellent chemical homogeneity of the final products [29–31]. In our previous work, we firstly reported the fabrication of TAG transparent ceramics using the co-precipitated powders [26] and investigated the influence of ammonium hydrogen carbonate to metal ions molar ratio on the properties of TAG nanopowders and the resultant ceramics [25]. Finally, we successfully fabricated highly transparent TAG magneto-optical ceramics from co-precipitated nanopowders with tetraethoxysilane (TEOS) as sintering aid by vacuum sintering combined with hot isostatic pressing (HIP) post-treatment [32]. The in-line transmittance of the ceramic sample is nearly 80% in the visible and near-infrared spectral regions, reaching 81.8% at the wavelength of 1390 nm. The Verdet constant at 633 nm for the TAG ceramic is −182.7 rad/(T·m), which is 36% higher than that of the commercial TGG single crystal (−134 rad/(T·m)). In 2017, Aung et al. successfully fabricated the $(Tb_xY_{1-x})_3Al_5O_{12}$ (x = 0.5–1.0) ceramics with ultralow optical loss and large scale by the solid-state

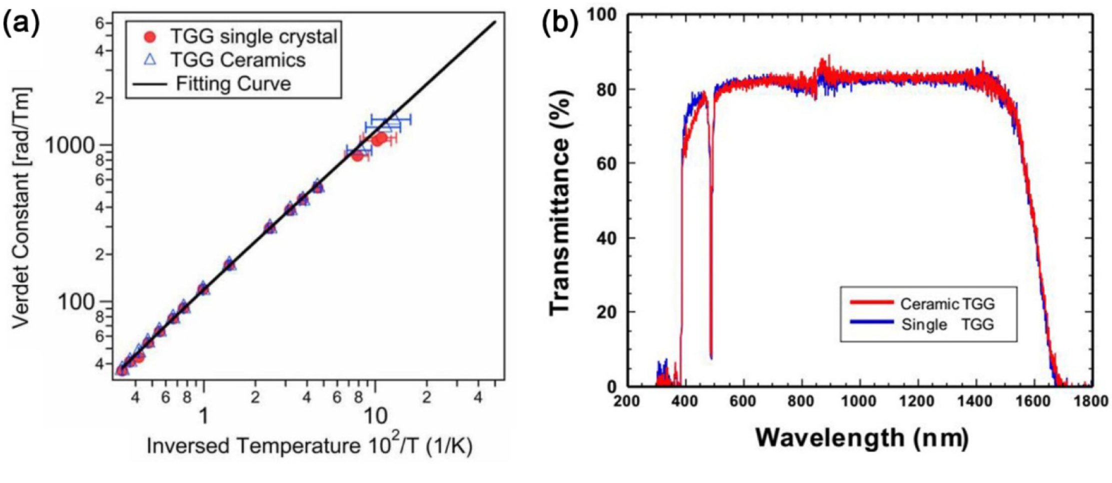

Fig. 1. (a) Temperature dependence of Verdet constant of TGG single crystal and TGG ceramics [11] and (b) Transmission spectra of the TGG single crystal and ceramic samples [7].