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A novel magneto-optical crystal Yb:$TbVO_4$

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ABSTRACT

Highly transparent Yb:$TbVO_4$ single crystal with dimensions of Ø27 × 41 mm^3 alomost without scattering defects has been successfully grown by Czochralski technique. The spectra, thermal properties and laser-induced damage threshold were investigated in detailed. The Faraday rotation (FR) measurement was carried out by means of extinction method. The Verdet constant comes up to 80 rad m^{-1} T^{-1} at 1064 nm, significantly larger than $TbVO_4$ (58 rad m^{-1} T^{-1}) and TGG (40 rad m^{-1} T^{-1}) reported. Meanwhile, the as-grown crystal presents lower absorption coefficient and higher magneto-optical figure of merit at measured wavelength in comparison with TGG. Moreover, the crystal exhibits a substantially improved extinction ratio (42 dB) in contrast with $TbVO_4$ (29 dB), and exceeds the highest value of TGG (40 dB). These advantages make Yb:$TbVO_4$ a highly promising magneto-optical material candidate for optical isolators in the visible-near infrared region.

1. Introduction

Optical isolators (OIs) based on the non-reciprocity of the Faraday effects play an increasingly important role in optic communication and optical measurement system [1–4]. They have been widely ultilized to prevent optical feedback from reaching and damaging the laser so as to guaranty an unidirectional light propagation in the laser systems [5,6]. With the rapid advance in high-power lasers and high-power fiber lasers, the demand for OIs operated in the visible-near infrared region has greatly increased [7–9]. For such devices, large Faraday rotation and high transmittance of the magneto-optical material are equally crucial. However, the conventional $Y_3Fe_5O_{12}$ (YIG) crystals are not applicable in 400–1100 nm owing to their poor transparency [10]. $Tb_3Al_5O_{12}$ (TAG) single crystal is thought to be a good candidate for such requirements because of its superior magneto-optical properties, while the practically applicable TAG crystal has not been grown by Czochralski method due to its incongruent melting nature [9]. Currently, the most commonly used magneto-optical crystal for OIs in the VIS–NIR is $Tb_3Ga_5O_{12}$ (TGG) crystal, which has been extensively investigated owing to its relatively large Verdet constant as well as good transmittance and high thermal conductivity [11]. Unfortunately, it is not easy to grow high quality TGG due to the component deviation induced by the comparatively high decomposition and evaporation of Ga_2O_3 during crystal growth [12,13].

Among the rare earth (RE) ions, Tb^{3+} ion exhibits the best magneto-optical properties [14,15]. Therefore, considerable research for exploring novel terbium-based magneto-optical materials has been conducted [1–4,16,17]. Additionally, previous studies have found that some paramagnetic RE (RE = Ce^{3+}, Pr^{3+}, Nd^{3+}, Yb^{3+} and so on) ions doped magneto-optical crystals, such as doped TGG, TAG and YIG, remarkably enhancing the magneto-optical performance because of the crystal field interaction and quantum-based super-exchange interaction between Tb^{3+} and other paramagnetic RE ions [18,19]. For instance, Ce^{3+}, Pr^{3+} and Nd^{3+} doped TGG exhibits 20–30% larger Verdet constant in comparison with that of TGG [4,18,19]. $Tb_3[Sc_{1.95}Lu_{0.05}](Al_3)O12$ garnet single crystals give rise to an increment of 20% of Verdet constant compared with TGG by doping Sc^{3+} and Lu^{3+} [20]. Besides, $(YYbBi)_3Fe_5O_{12}$ crystals possess larger Faraday rotation and smaller temperature derivative of Faraday rotation by substituting Bi^{3+} and Yb^{3+} [21–23].

$TbVO_4$ single crystal appeared very recently, it could be grown by Czochralski method and the bulk crystal growth is easier than TGG. Some researchers have successfully grown pure $TbVO_4$ crystal with 50% larger Verdet constant compared to TGG [24,25]. However, RE ions doped $TbVO_4$ has not been reported yet. Both Tb^{3+} and Yb^{3+} belong to paramagnetic RE ions, Tb^{3+} has a larger ionic radius than Yb^{3+} so Yb^{3+} could be incorporated into Tb^{3+} site, and we expect that Yb^{3+} doped $TbVO_4$ with larger Verdet constants at some wavelengths can be obtained due to super-exchange interaction. Accordingly, the present study aimed at enhancing the Faraday effect of $TbVO_4$ by substituting Yb^{3+} for Tb^{3+} and growing high quality crystal

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without scattering defects simultaneously. In this article, we firstly report the growth of Yb:$TbVO_4$ crystal by Czochralski method, the crystal quality, spectrum, thermal properties, LIDT and magneto-optical properties were analyzed in detailed.

2. Experimental procedure

2.1. Crystal growth

Polycrystalline materials $TbVO_4$ and $YbVO_4$ used were synthesized by the liquid-phase reaction method. These compounds were weighted accurately according to the following ratios: $Yb_{0.1}Tb_{0.9}VO_4$ (10-at.% Yb doping concentration). Yb:$TbVO_4$ single crystal was grown by Czochralski method in a Ø65 × 40 mm^3 iridium crucible under the protect of high purify nitrogen atmosphere. In our experiments, all crystals were grown along the [0 0 1] direction using a pure $TbVO_4$ crystal sample as the seed crystal at a pulling rate of 1–1.5 mm/h and a rotation rate of 6–12 rpm. After growth, the crystal was drawn out of the melt surface and cooled down to room temperature at an appropriate cooling rate.

2.2. Characteristics

The powder X-ray diffraction (XRD) measurement was examined by a computer-automated diffractometer (Bruker D8 Focus) equipped with Cu K_α radiation (λ = 1.54,056 Å) at room temperature. A step size of 0.02 and counting time of 0.1 s/step were applied in the 2θ range of 10–90°.

The concentration of Yb^{3+} ion in the crystal was analyzed using the inductively coupled plasma and optical emission spectrometry (ICP-OES) method. The sample was cut from the middle part of the as-grown crystal. The effective Yb^{3+} segregation coefficient K_{eff} can be calculated by the following equation: $K_{eff} = C_s/C_l$, where C_s is the Yb^{3+} concentration in the crystal, and C_l is the initial Yb^{3+} concentration in the melt.

The as-grown crystal was cut along (0 0 1) plane oriented by XRD, then ground and polished carefully to about 1 mm thickness for spectra measurement. The transmission spectrum was measured using a Perkin-Elmer Lambda 900 UV–Vis-NIR Spectrophotometer at wavelength of 400–3000 nm. A rectangular prism with an angle of 15° was cut to determine the refractive index of as-grown crystal by a SpectroMaster UV–Vis-IR.

The thermal expansion coefficient was determined employing a thermo-mechanical analyzer (Perkin-Elmer TMA) in the temperature range of 25–500 C at a heating rate of 10 °C/min. The thermal diffusion coefficient and specific heat were performed between 20 and 300 °C using a laser flash apparatus (NETZSCH LFA 447 Nanoflash) and a differential scanning calorimeter (Diamond DSC-ZC), respectively. The Laser-induced damage threshold (LIDT) testing was carried out using Nd:YAG laser system at 1064 nm with a pulse repetition rate of 1 kHz and the pulse duration of 5 ns. The (0 0 1) surfaces of 5 × 5 mm^2 were optically polished for LIDT measurement.

The optical weak absorption of as-grown crystal along c axis was measured at 1064 nm by photothermal common-path interferometer (PCI) technique [26]. The size of the sample used for the measurement was 5 × 5 × 5 mm^3.

The X-ray photoelectron spectroscopy (XPS) was recorded using Thermo Scientific ESCALAB 250Xi for valence state analysis of elements.

The Faraday rotation (FR) measurement of the Yb:$TbVO_4$ crystal along c axis was carried out by extinction method [27] and the magnetic field intensity ranged from 0 to 1.2 T. Lasers of 532, 633 and 1064 nm were used as the sources of the probe beam. A sample with dimensions of 3 × 3 × 15 mm^3 was employed and two 3 × 3 mm^2 faces were optically polished.

3. Results and discussion

3.1. The influence of cooling rate on optical quality

The as-grown Yb:$TbVO_4$ single crystals, shown in Fig. 1, are transparent and inclusions free with a slight yellow. Detailed growth results are listed in Table 1.

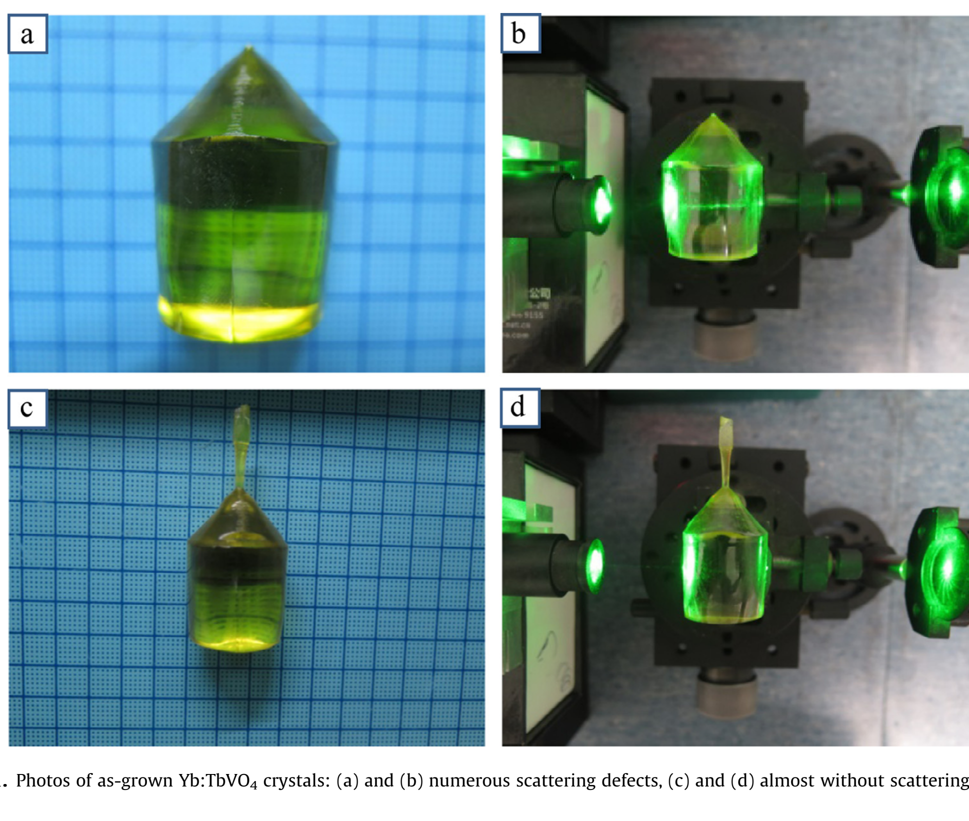

Fig. 1. Photos of as-grown Yb:$TbVO_4$ crystals: (a) and (b) numerous scattering defects, (c) and (d) almost without scattering defects.