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Spectroscopy and laser performance of Yb^{3+}:$GdMgB_5O_{10}$ crystal

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ABSTRACT

A bulk crystal of Yb-doped $GdMgB_5O_{10}$ was firstly grown successfully by the top seeded solution growth method. The spectroscopic properties were characterized in terms of polarized absorption and fluorescence spectra, and lifetime measurement. Stark energy level diagram for the Yb^{3+}:$GdMgB_5O_{10}$ crystal was analyzed. Corresponding absorption and emission cross-sections, the gain cross-sections were calculated. A maximum laser output power 5.35 W was attained with corresponding to an optical-to-optical efficiency of 50.8% and a slope efficiency of 56%. The results show that Yb^{3+}:$GdMgB_5O_{10}$ crystal is a promising laser medium.

1. Introduction

Over the last few decades, Yb-doped laser crystals have been recognized to be ideal candidates for compact efficient diode-pumped lasers emitting at ~1 μm range [1–3]. The trivalent Yb^{3+} ion has only two energy level manifolds ($^2F_{7/2}$ and $^2F_{5/2}$), which are beneficial to eliminate the undesired effects, such as excited state absorption, up-conversion, cross-relaxation process and concentration quenching [4–7]. Currently, various Yb-doped materials have been successfully prepared to generate laser operation, such as the garnets Yb:YAG, the silicates Yb:Gd_2SiO_5, the tungstates Yb:$KGd(WO_4)_2$ and Yb:$KY(WO_4)_2$, and the borates Yb:$YAl_3(BO_3)_4$, Yb:$Sr_3Y_2(BO_3)_4$ and Yb:$YCa_4O(BO_3)_3$ [8–14].

Recently a new borate $LaMgB_5O_{10}$ (LMB) crystal with a special structure of the infinite two-dimensional $[B_5O_{10}]^{5-}{}_n$ layers, which has good thermal conductivity and optical properties, was proved as an ideal laser host [15,16]. A Yb^{3+}-doped LMB crystal with high optical quality was grown, and a 2.76 W continuous-wave (CW) laser output power at 1057 nm with a slope efficiency of 64.5% was performed. However, as the difference of ionic radius between La^{3+}(1.216 Å) and Yb^{3+}(0.985 Å) ions is large, it is not easy for Yb^{3+} ions to substitute for La^{3+} ions in LMB crystal, which leads to a small segregation coefficient of Yb^{3+} ions as only 0.34 in LMB crystal [17]. The small segregation coefficient indicates that it is difficult to obtain a high Yb^{3+} concentration doped crystal. As Yb^{3+} ion has low fluorescence concentration quenching, a high Yb doped concentration ($\sim 1\times10^{21}$ ions/cm^3) gain media is much suitable for obtaining high efficient laser oscillation [11,14]. The $GdMgB_5O_{10}$ (GMB) compound crystallizes in monoclinic, space group *P21/n* with a = 8.623 Å, b = 7.586 Å, c = 9.377 Å, β = 93.19(3)° and V = 612.5(2) Å^3 [18]. The GMB crystal may provide preferable condition for Yb^{3+} ions because the Gd^{3+}(1.053 Å) ion is closer to that of Yb^{3+} ions. Therefore, the GMB crystal may be a better laser host than LMB crystal. In this paper, the growth, spectral properties and CW laser performance of Yb:GMB crystal are reported.

2. Experiment details

The Yb:GMB crystals were grown using the top seeded solution growth (TSSG) method from a flux of $K_2Mo_3O_{10}$ in a vertical tubular furnace. The furnace temperature was controlled by an AL-808 controller with a controlling accuracy of ± 0.1 K. The raw materials were weighed according to the molar ratio of Yb:GMB to $K_2Mo_3O_{10}$, which is 1: 2. The chemicals used were analytical-grade K_2CO_3, MgO, H_3BO_3 and MoO_3 as well as Gd_2O_3 and Yb_2O_3 with 99.99% purity. The growing procedure was as follows: the weighed raw materials were ground thoroughly and then put into a platinum crucible with dimensions of Ø50 × 60 mm^3. The melt was heated to 1100 °C and held for two days to make the solution melt completely and homogeneously. The saturation temperature was determined to be exactly 952 °C by the repeated seeding trials and the crystal was grown at a cooling rate of 0.5–1/day and a rotating rate of 45 rpm. When the growth ended, the crystals were drawn out of the solution and cooled down to room temperature at a rate of 20 °C/h. A transparent crystal with dimensions of 20 × 15 × 10 mm^3 was grown, as shown in Fig. 1. The Yb:GMB crystal

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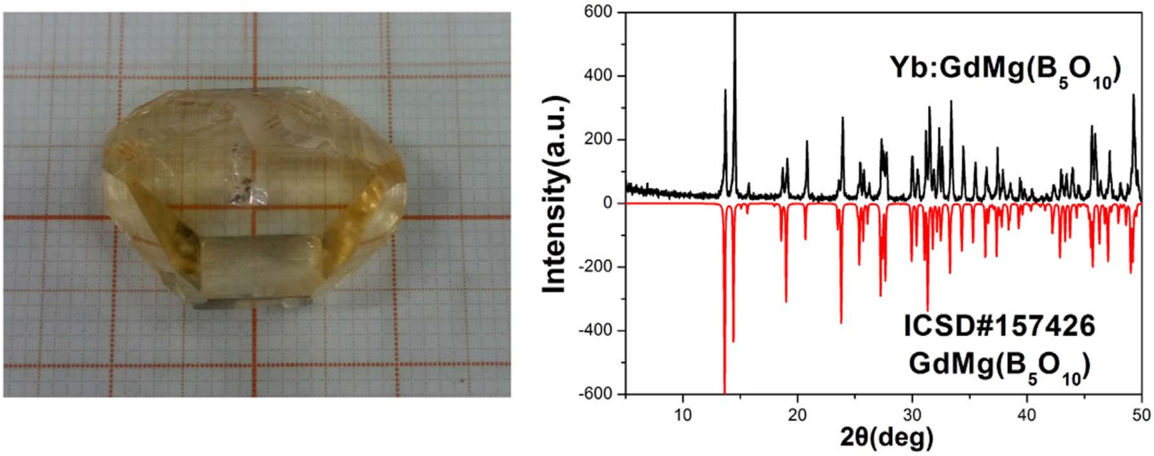

Fig. 1. Yb:GMB crystal and the powder X-ray diffraction pattern. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

displays slightly brown-yellowish color, which may be caused by Mo ions impurity when borate crystals used $K_2Mo_3O_{10}$ as a flux [19]. The powder X-ray diffraction pattern of the crystal was determined by Miniflex600 diffractometer with Cu-Kα (λ = 1.54056 Å). The result was consistent with the standard pattern of $GdMgB_5O_{10}$ crystal grown by NaF flux (ICSD#157426), which confirmed that the as-grown crystal was GMB crystal and there were no significant change of structure after the large amount of Yb^{3+} ions were doped into the crystal [18]. The concentration of Yb^{3+} ion was determined to be 13.05 at% or 8.52×10^{20} ions/cm^3 by the inductively coupled plasma atomic emission spectrometry (ICP-AES, Ultima2, Jobin-Yvon). As the initial Yb concentration was 20.0 at% in the solution, then the segregation coefficient was calculated as 0.65, which is much larger than the value 0.34 of Yb:LMB crystal [15]. This is in accordance with the aforementioned that GMB crystal is more suitable for Yb ion doping than LMB crystal.

The crystal orientations were determined by the YX-200 X-ray diffraction orientating instrument. The optical indicatrix axes orientation were observed by polarization microscope using a Na lamp (λ = 589.6 nm). A sample with dimension of $6.00 \times 5.28 \times 4.60$ mm^3 cut from the as-grown Yb:GMB crystal along the optical indicatrix axes was polished well and used for spectral measuring. The sketch of the relationship between crystallography axes and optical indicatrix axes is shown in Fig. 2, the E-vector was oriented paralleling to the X, Y and Z-axes in the experiments. The polarized absorption spectra were recorded using a Perkin-Elmer spectrophotometer (Lambda 950) in a range of 850–1150 nm. The polarized fluorescence spectra and fluorescence lifetime were measured using an Edinburgh Analytical Instruments FLS980 Fluorescence spectroscopy excited with 937 nm radiation. The spectral resolutions were 0.5 nm in both the absorption and emission measurements.

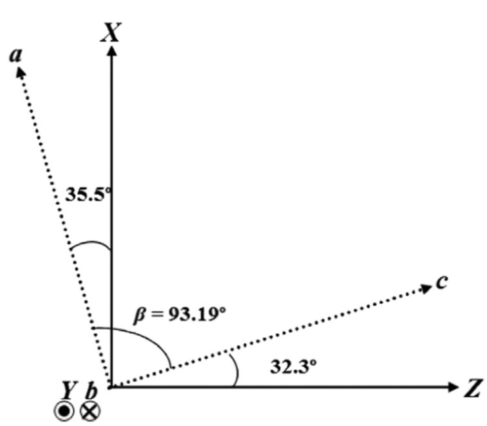

Fig. 2. Relationship between the optical and crystallography axes.

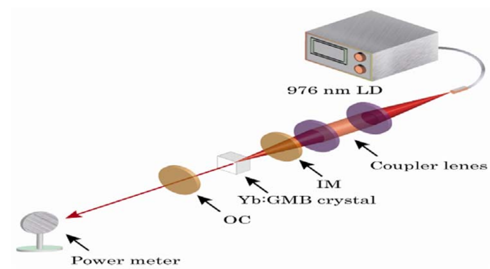

Fig. 3. Schematic diagram of LD-end-pumped Yb:GMB laser.

The CW laser of the Yb:GMB crystal was realized by using a plano-concave resonator, as shown in Fig. 3. The dimensions of the Yb:GMB crystal was $3 \times 3 \times 2$ mm^3 with both sides polished and no anti-reflection coated. The crystal was wrapped with indium foil and held in a copper block maintaining the temperature at 25 °C by water cooler. The pumping source was a 976 nm fiber-coupled LD delivering a maximum pump power of 30 W. The core diameter and numerical aperture of LD were 200 μm and 0.22, respectively. The pump light was re-imaged into the gain medium with a spot size of about 200 μm in diameter by a simple 1:1 telescopic lens system. The input mirror IM was a concave mirror having a radius of 2000 mm with high reflection (HR, R > 99.8%) at 1020–1080 nm and high transmission (HT, T > 90%) at 976 nm. The output coupler (OC) was a plane mirror with the transmittance of 3% at 1020–1080 nm. The laser cavity length was about 15 mm. The laser output power was measured by using a thermopile power meter (LPE-1B) and the laser spectra were recorded with a spectrometer (HR4000, Ocean Optics). The laser beam spatial structure was investigated by using an IR-sensitive camera Pyrocam III (Ophir Optronics Ltd).

3. Results and discussions

3.1. Spectral characteristics

Fig. 4 shows the polarized absorption spectrum of Yb:GMB crystal at room temperature. There are three absorption bands due to the transition of $^2F_{7/2} \rightarrow {}^2F_{5/2}$. The absorption bands centered at 914, 937, and 975 nm are attributed to the 1→7, 1→6, and 1→5 transitions, respectively, where number from 1 to 7 (in the order of increasing energy) are labeled as sublevels of the $^2F_{7/2}$ ground state and $^2F_{5/2}$ excited state, respectively. The absorption cross-sections at 975 nm were calculated to be 1.20×10^{-20} cm^2 for E//Z, 1.25×10^{-20} cm^2 for E//Y and 0.35×10^{-20} cm^2 for E//X. The polarized fluorescence spectrum of Yb:GMB crystal at room temperature is also shown in Fig. 4.