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Short communication

Diode-side-pumped 1123 nm Nd:YAG ceramic laser

Wenbin Liu[a,b], Di Zhang[a,*], Yanping Zeng[b], Jiang Li[b], Yubai Pan[b,**], Jingkun Guo[b], Yong Bo[c], Qinjun Peng[c], Zuyan Xu[c]

[a]*State Key Laboratory of Metal Matrix Composites, Shanghai Jiao Tong University, Shanghai 200240, China*
[b]*Key Laboratory of Transparent Opto-functional Inorganic Materials, Shanghai Institute of Ceramics, Chinese Academy of Sciences, Shanghai 200050, China*
[c]*Key laboratory of Functional Crystal and Laser Technology, Technical Institute of Physics and Chemistry, Chinese Academy of Sciences, Beijing 100190, China*

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Abstract

Transparent Nd:YAG ceramics were fabricated by solid-state reactive sintering, a mixture of commercial Al_2O_3, Y_2O_3, and Nd_2O_3 powders, and their microstructure and optical properties were investigated. A fully dense 1.0 at. % Nd:YAG ceramic with an average grain size of ~15 μm was obtained by vacuum sintering at 1750 °C for 50 h. The optical in-line transmittance of the corresponding sample was very close to that of single crystal. Diode-side-pumped laser operation with two ceramic rods (Ø6 × 100 mm^2) was demonstrated. When the pump power was 2000 W, the output power of 509 W at 1123 nm for Nd:YAG ceramic laser was obtained, and the optical-to-optical conversion efficiency was 25.5%. 509 W is the highest laser output power for an Nd:YAG laser (including ceramic and single crystal) operating at 1123 nm to date.

Keywords: B. Microstructure; B. Grain boundaries; C. Optical properties; 1123 nm laser output

1. Introduction

Transparent Nd:YAG ceramics have received considerable attention because the optical properties have been improved greatly and the highly efficient laser oscillations have been obtained, whose efficiencies are comparable or superior to those of single crystals. Moreover, the fabrication technology of Nd:YAG ceramics possesses numerous advantages over single crystals, such as lower price, ease of manufacture, higher concentration doping, and the ability to be fabricated to large size with complicated structures [1–9]. However, numerous approaches to Nd:YAG ceramics are focused on the $^4F_{3/2} \rightarrow {}^4I_{11/2}$ transition at 1064 nm, $^4F_{3/2} \rightarrow {}^4I_{13/2}$ transition at 1319 nm and $^4F_{3/2} \rightarrow {}^4I_{9/2}$ transition at 946 nm [5–7]. Besides these frequently used laser radiations, Nd:YAG lasers can also operate at 1112 nm, 1116 nm, and 1123 nm, which correspond to the Stark components of the $^4F_{3/2} \rightarrow {}^4I_{11/2}$ transition [8]. In recent years, there has been great interest in 1123 nm Nd:YAG lasers with high output power owing to their wide applications. For example, the yellow–green laser at 561 nm from the frequency-doubled 1123 nm line has important applications in biology and biomedicine [9]. Nd:YAG lasers operating at 1123 nm can be used as a pump source for thulium upconversion fiber lasers to generate blue light lasers, which are required for RGB color displays, printing and data recording [10].

In the present work, Nd:YAG ceramics were fabricated by solid-state reaction and vacuum sintering using commercial powders. The effects of different sintering conditions on microstructure and optical properties of Nd:YAG

*Correspondence to: State Key Laboratory of Metal Matrix Composites, Shanghai Jiao Tong University, 800 Dong-Chuan Road, Shanghai 200240, PR China. Tel.: +86 21 34202634; fax: +86 21 34202749.
**Correspondence to: Key Laboratory of Transparent Opto- functional Inorganic Materials, Shanghai Institute of Ceramics, Chinese Academy of Sciences, 1295 Ding-Xi Road, Shanghai 200050, PR China. Tel.: +86 21 52412820; fax: +86 21 52413903.
E-mail addresses: zhangdi@sjtu.edu.cn (D. Zhang), ybpan@mail.sic.ac.cn (Y. Pan).

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ceramics were studied. The laser performances of Nd:YAG ceramics using a diode-side-pumped system with a plano–plano symmetrical cavity were demonstrated.

2. Experimental procedure

2.1. Material fabrication

Commercial high-purity powders of α-Al_2O_3 (>99.99%, Alfa Aesar Company, USA), Y_2O_3 (>99.99%, Alfa Aesar Company, USA) and Nd_2O_3 (>99.99%, Alfa Aesar Company, USA) were used as starting materials. These powders were weighted in accordance with the chemical composition of $Nd_{0.03}Y_{2.97}Al_5O_{12}$ (1.0 at% Nd:YAG). All components were mixed by ball milling with high-purity Al_2O_3 balls for 12 h in ethanol using tetraethyl orthosilicate (TEOS, >99.99%, Alfa Aesar Company, USA) as a sintering aid. The slurries were dried and sieved through a 200-mesh screen. The powders were unaxially pressed into Ø170 mm disk at 100 MPa, and then cold-isostatic-pressed under 250 MPa.The compacted pellets were sintered in a tungsten mesh-heated vacuum furnace under 10^{-5} Pa vaccum during holding, and then annealed at 1450 °C for 20 h in air to decolor the samples. Finally, highly transparent Nd:YAG ceramics were obtained. Mirror-polished samples on both surfaces were used to measure optical transmittances (Model Cary-5000, Varian, USA). Microstructure of the samples was observed by a electron probe microanalyzer (EPMA, Model JXA-8100, JEOL, Japan).

2.2. Theoretical analysis

The typical energy level diagram of Nd:YAG ceramic is shown in Fig. 1. There exist three lines in a narrow region that are 1112 nm, 1116 nm, and 1123 nm, respectively, besides of three strong transitions at 946 nm, 1064 nm, and 1319 nm. Hence, in order to obtain single 1123 nm wavelength laser output, the other wavelength oscillations must be restrained by means of precise coating and adjusting the rotating angle of the etalon in the laser system [11].

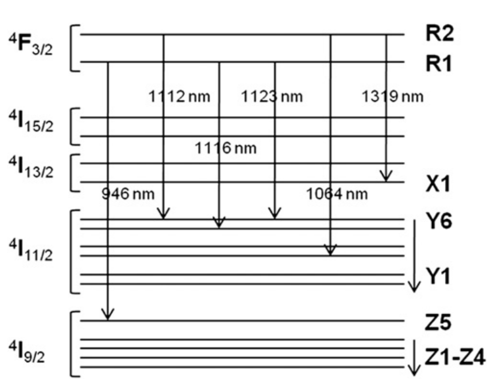

Fig. 1. Typical energy level diagram of Nd:YAG ceramics.

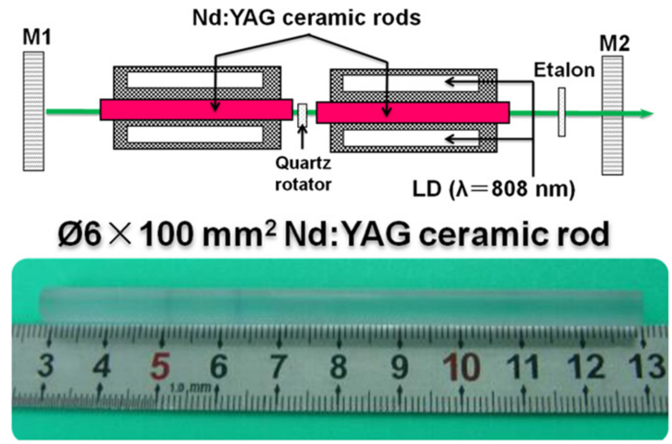

Fig. 2. Experimental configuration of laser system (upper) and photo of Nd:YAG ceramic rod (lower).

2.3. Laser experiment

Experimental configuration of the Nd:YAG ceramic rod laser is shown in Fig. 2 (upper). Two laser modules are placed in the laser system to supply higher pump power. Each module contains a 1.0 at% Nd:YAG ceramic rod with dimension of Ø6 × 100 mm^2 (shown in Fig. 2 (lower)). For each laser module, a home-made 30 LD-bars array arranged in a five-fold symmetry around the ceramic rod is served as pump source operated at the emission wavelength of 808 nm. The maximum pump power for each module is 1000 W. Both end facets of the ceramic rods are mirror-polished and antireflection coated at 1123 nm. The input mirror (M1) of the laser cavity is having 90% transmittance at 808 nm and 99.8% high-reflection ratio at 1123 nm. M2 is an output coupling mirror (OC) with transmittance of 5% at 1123 nm and high-transmittance ($T>85\%$) at 946 nm, 1064 nm and 1319 nm.

3. Results and discussion

Fig. 3(a) and (b) shows the EPMA morphologies of 1.0 at% Nd:YAG ceramics sintered at 1750 °C for 50 h and 100 h under vacuum. There are no traces of pores or secondary phases in both samples. The average grain sizes are 15 μm and 20 μm. It means that the longer the holding time, the larger the grain sizes. When the sintering temperature is increased to 1770 °C, abnormal grain growth is observed, and some pores will be trapped in and between the grains, as showed in Fig. 3(c).

The optical qualities of Nd:YAG ceramics are closely related to their microstructure. The transmittances of Nd:YAG ceramics with different sintering conditions are shown in Fig. 4. For the samples sintered at 1750 °C for 50 h and 100 h, their optical transmittances both hit the upper limit of the theoretical values of Nd:YAG single crystal in spite of the different holding time [12]. The result indicates that the average grain size increases from 15 μm to 20 μm (Fig. 3(a) and (b)) with the increasing of the

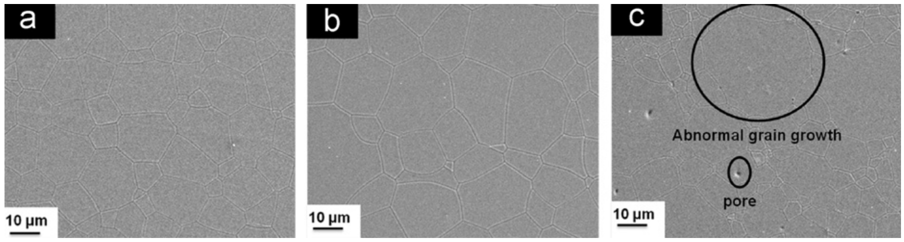

Fig. 3. Microstructure of Nd:YAG ceramics sintered at different conditions: (a) 1750 °C for 50 h, (b) 1750 °C for 100 h, and (c) 1770 °C for 50 h.

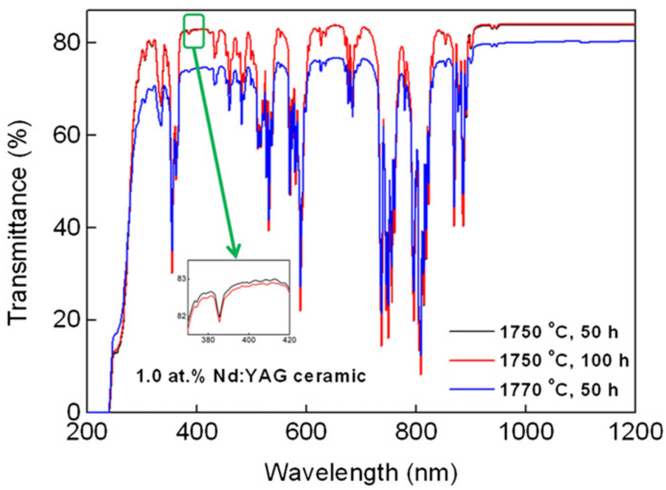

Fig. 4. Transmittances of Nd:YAG ceramics sintered at different conditions.

holding time after removing the pores from the Nd:YAG ceramics, which should not decrease the optical quality of the sample. The experimental conclusions are in good agreement with the previous reports [13]. But the larger grain size will degrade the hardness and fracture toughness of the ceramic [14], and then increase the possibility of thermal cracking, especially under high-power-pumped condition. The sample sintered at 1770 °C for 50 h shows a lower transparency, the dropoff in transmittance attributes to the scattering loss mainly caused by a very small quantity of pores (Fig. 3(c)) in the ceramic.

The high-resolution TEM micrographs of the grain boundaries of the samples vacuum-sintered at 1750 °C for 50 h and 100 h are shown in Fig. 5(a) and (b). The grain boundaries of two samples are clear and clean. The widths of both the grain boundaries are less than 1 nm, which are much smaller than the laser wavelength of 1064 nm. In this case, the total scattering losses caused by the grain boundaries can be ignored [15].

Taking all the above theories and experimental results into consideration, the sample sintered at 1750 °C for 50 h is chosen to exhibit the laser performance at 1123 nm. The laser output power for Nd:YAG ceramic versus pump power is shown in Fig. 6. The linear relation between the output power and the pump power is observed. The threshold power is about 298 W. The output power is 509 W at a maximum pump power of 2000 W with an optical-to-optical conversion efficiency of 25.5%. So far 509 W is the highest output power for 1123 nm Nd:YAG laser (including ceramic and single crystal). There is no obvious evidence of saturation from the output power curve, which means higher output power at 1123 nm is possible if higher pump power is supplied. In addition, two Nd:YAG ceramic rods with high optical quality are used to study the laser performance at 1064 nm under the identical diode-side-pumped condition. We only change the coating parameters as follows: the both facets of the ceramic rods are high transmission coated at 1064 nm. M1 is antireflection (90%) coated at 808 nm and high reflection (99.8%) at 1064 nm and M2 is coated at different transmissions. When the pump power is 2000 W, a maximum output power of 794 W is obtained, corresponding to an optical-to-optical conversion efficiency of 39.7%. Inferior laser performance at 1123 nm than that at 1064 nm is because the conversion of the upper-state energy to laser output of each wavelength is solely determined by the stimulated emission cross sections. The stimulated emission cross section at 1123 nm is approximately 15 times smaller than that at 1064 nm [8].

As is well known, a laser tends to oscillate on the line with lowest threshold; the threshold powers are related to the transmittances of the output coupler mirror (M2). When the output coupler has HT coatings at 964 nm, 1064 nm and 1319 nm, and higher transmittances at 1112 nm (T=7.8%) and 1116 nm (T=6.5%) than that at 1123 nm (T=5%), the 1123 nm laser line first reaches threshold and starts oscillation, and then consumes the energy from the gain medium. Subsequently, the gain decreases in turn owing to the gain saturation effects. Thus the laser oscillations at 946 nm, 1064 nm, 1112 nm, 1116 nm, and 1319 nm could be restrained, only 1123 nm laser line is found in the output spectrum with a wavelength span from 900 nm to 1400 nm (Fig. 7).

4. Conclusions

Transparent Nd:YAG ceramics were fabricated with different holding times and sintering temperatures in the vacuum-sintering procedure. The sample sintered at 1750 °C for 50 h has a fine microstructure, with a uniform grain size of 15 μm and there are no obvious pores and secondary phases in or between the grains. The corresponding in-line transmittance hits the upper limit of the

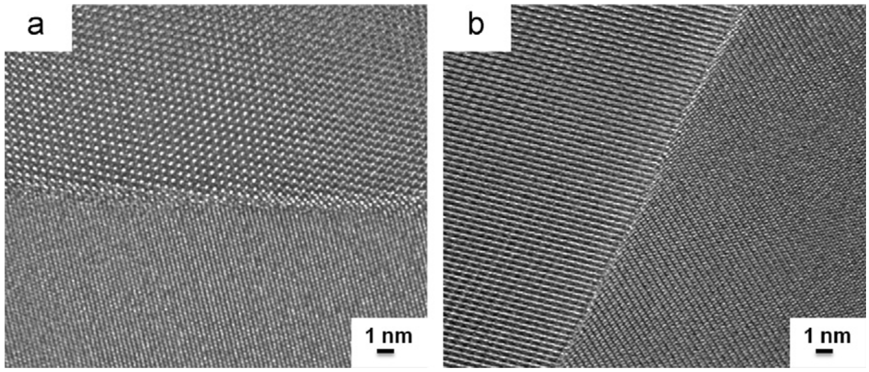

Fig. 5. High-resolution TEM micrographs of the grain boundaries of the samples vacuum-sintered at 1750 °C for 50 h (a) and 100 h (b).

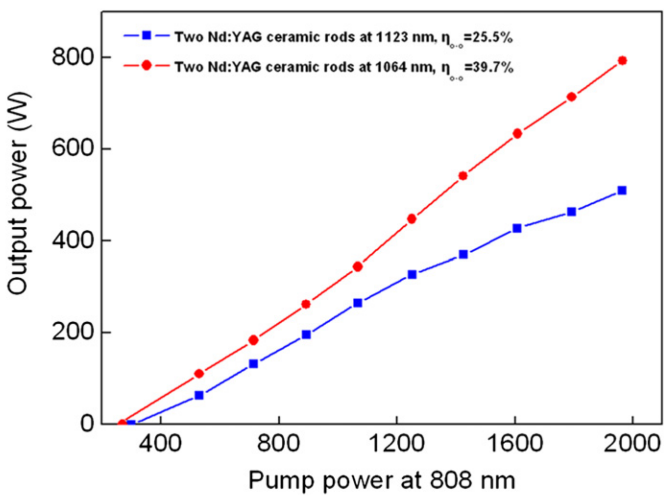

Fig. 6. Laser output power for Nd:YAG ceramics sintered at 1750 °C for 50 h versus incident pump power at 808 nm.

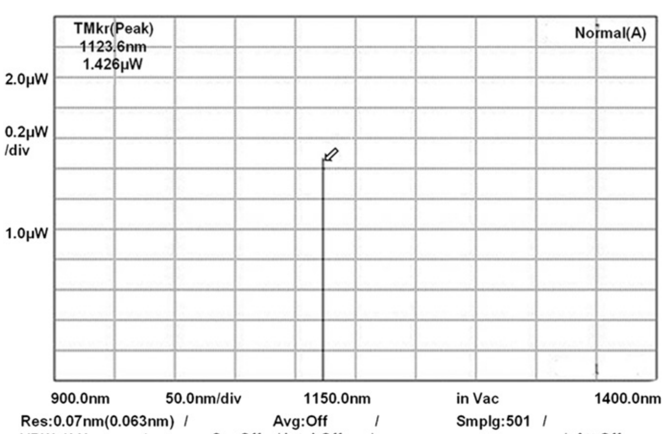

Fig. 7. Spectrum of the 1123 nm Nd:YAG ceramic laser in the wavelength range 900–1400 nm.

theoretically calculated values. Under the pump power of 2000 W, the output powers are 509 W at 1123 nm and 794 W at 1064 nm for Nd:YAG ceramic laser, the optical-to-optical conversion efficiencies are 25.5% and 39.7%, respectively. To the best of our knowledge, this is the highest output power of 1123 nm Nd:YAG laser to date. The results show the Nd:YAG ceramic is an appropriate material for 1123 nm laser generation.

Acknowledgments

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