6.8-W High Efficiency Yb:YAG Ceramic Laser at Room Temperature

Shinki NAKAMURA, 1 Hiroaki YOSHIOKA, 1 Yu MATSUBARA, 1 Takayo OGAWA, 2 and Satoshi WADA 2

1Department of Media and Telecommunications Engineering, Faculty of Engineering, Ibaraki University, 4-12-1 Nakanarusawa, Hitachi, Ibaraki 316-8511
2The Institute of Physical and Chemical Research (RIKEN), 2-1 Hirosawa, Wako, Saitama 351-0198

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A high-power efficient ceramic Yb:YAG laser was demonstrated at a room temperature of 20°C with an Yb concentration of 9.8 at.%, a gain medium of 1 mm, a pumping power of 13.8 W, an output coupler of T = 10%, and a cavity length of 20 mm. A 6.8 W cw output power was obtained with a slope efficiency of 72%. The ceramic Yb:YAG laser exhibited a continuous tunability in the spectral range of 63.5 nm from 1020.1 to 1083.6 nm for T = 1% at a maximum output power of 1.6 W. To the best of our knowledge, this is the first study of the tunability of ceramic Yb:YAG lasers, except crystal Yb:YAG studies.

Key Words: Yb:YAG, Ceramic laser, High efficiency, High power, Tunable

1. Introduction

Ceramic laser media fabricated by vacuum sintering 1)-3) and nanocrystalline 3) technology are very attractive materials because they have several remarkable advantages compared with single crystal laser materials. Ceramic samples with a large size can be easily fabricated, whereas this is extremely difficult for single crystals; multiplayer and multifunctional ceramic laser materials are possible because of the polycrystallinity of ceramics. 3) Potentially, because of their short fabrication period and because they can be mass-produced, the cost of ceramic laser materials could be much lower than that of single crystals. Furthermore, no complex facilities and critical techniques are required for the growth of ceramics. Since 1995, Ikesue and coworkers have been developing several types of ceramic laser material, 1), 2) and they found that the output power from a 3.4 at.% Nd:YAG ceramic microchip laser is twice that from a Nd:YAG crystal microchip laser of the same size in 2000. 5) At a low doping concentration, it was found that the efficiency of a diode-end-pumped Nd:YAG ceramic laser is even higher than that of a Nd:YAG single crystal laser. Since 1998, Yanagitani and coworkers have been developing several types of ceramic lasers, and Lu et al. reported the Nd:YAG ceramic laser as one of them in 2001. 6) The mechanical properties of YAG ceramics were reported in ref. 7. YAG ceramics had a 10% higher hardness than a YAG single crystal, and the fracture toughness of the YAG ceramics was more than threefold that of the YAG single crystal. Therefore, the ceramics had a higher resistance to thermal shock than the single crystal. Ytterbium (Yb 3+)-doped materials are very attractive for diode-pumped solid-state lasers (DPSSLs). 8) The Yb 3+-doped materials have high quantum efficiency and exhibit no concentration quenching simply because the Yb 3+ ion has only two manifolds, namely, the ground state 2F 7/2 and the upper level 2F 5/2. Thus far, many articles about Yb:YAG crystal lasers have been published. 9)-11) Yb:YAG has broad absorption and emission bands. The broad absorption band in the near-IR region is suitable for laser-diode (LD) pumping, and the broad emission band enables the generation of ultrashort pulses. 10) However, an Yb:YAG laser is known as a quasi-three-level laser or a quasi-four-level laser, and a finite population exist at the Stark level of the lower manifold 1F 2, which requires high-intensity pumping, a high-brightness pump source, and an efficient heat removal technique 11) to prevent reabsorption from the lower level of the laser. Takaichi et al. reported the absorption and emission spectra of a Yb:YAG ceramic (C Yb = 1 at.%) and demonstrated laser oscillation, which was the first diode-end-pumped Yb:YAG ceramic laser (not Nd:YAG) with a 345 mW cw output power and a slope efficiency of 26%. 12) Recently, Tsunekane and Taira have demonstrated a high-power diode-edge-pumped single-crystal Yb:YAG / ceramic undoped YAG composite microchip laser. 13), 14) Early in 2007, a diode-edge-pumped, composite all-ceramic Yb:YAG (C Yb = 10 at.%) microchip laser was demonstrated by Tsunekane and Taira, and a 414 W cw output power was obtained with a slope efficiency of 47%. 15) Very recently, Dong et al. have demonstrated a 2.7 W heavily doped (20 at.%) Yb:YAG ceramic laser with a slope efficiency of 52% 16) ; however, its two-pass-pumping miniature laser configuration was more complex than a simple conventional end-pumping configuration and its output power was not markedly high. Nakamura et al. demonstrated a 5.5 W cw Yb:YAG (9.8 at.%) ceramic laser with a slope efficiency of 52% using a simple end-pumping scheme 17) with a 400 μm fiber-coupled LD. Dong et al. demonstrated a highly efficient (a slope efficiency of 79%) Yb:YAG ceramic laser 20) with a 100 μm fiber-coupled LD using an end-pumping scheme, but its output power was 1.7 W.

In this paper, we report a high-power (6.8 W) and high-efficiency tunable Yb:YAG ceramic laser demonstrated using an end-pumping scheme with a slope efficiency of 72% at room temperature (20°C). In the previous reports of Yb:YAG ceramic lasers, no description of the tunability of the lasers is given. However, there are some reports about the...
The experimental setup for Yb:YAG ceramic laser is shown in Fig. 1. A 940 nm fiber-coupled LD (JENOPTIK Laserdiode, JOLD-30-FC-12) was used as a pumping source, the core diameter of the fiber was 200 μm, and the numerical aperture (NA) of the fiber was 0.22. The pumping beam was focused onto the ceramic with a ratio of 1:1 using the lenses L1 (f' = 25 mm) and L2 (f' = 25 mm). The diameter of the focused spot on the ceramic was ~200 μm. To obtain high efficiency and high power, a laser cavity consisting of a flat dichroic mirror (DM) and a flat output coupler (OC) as a linear resonator (without a mirror M and an SF10 prism) was used. The DM was antireflection (AR)-coated at 940 nm and had a high reflectivity at 1030 nm. The OC was partially-reflection-coated with a transmittance of T = 1, 5, and 10% at 1030 nm. An AR-coated ceramic Yb:YAG (C_{Yb} = 9.8 at.%; Konoshima Chemical) with dimensions of 5x10x1 mm³ was used. A 1-mm-thick Yb:YAG ceramic plate was wrapped with indium foil and mounted in a water-cooled copper block that acted as a heat sink. Water was maintained at a room temperature of 20ºC during laser oscillation. The cavity length was 20 mm, which was optimized, as shown in the later part of this letter. Figure 2 shows the dependence of the output power on the absorbed pump power, which was determined by considering the absorption efficiency difference between non-lasing and lasing cases, i.e., absorption efficiency remains constant with an increase in pump intensity in the lasing case.12

3. Experimental results

Figure 2(a) shows the cases for the three transmittances of the output couplers T = 1, 5, and 10%, and Fig. 2(b) shows only the case of T = 10%. The absorbed pump powers at the lasing threshold were 1.2, 2.0, and 2.3 W, and the maximum output powers of 6.9, 6.9, and 6.8 W for T = 1, 5, and 10%, respectively, were obtained at the absorbed pump power of 13.8 W. Each linear line was fit in Fig. 2(a) for T = 1, 5, and 10%. The slope efficiencies η_{slope} were 60, 64, and 72% for T = 1, 5, and 10%, respectively. Since we considered that T = 10% is best for obtaining the highest slope efficiency of 72%, we filled the data for the T = 10% case to Fig. 2(b). The maximum output power of 6.8 W for T = 10% was obtained at the absorbed pump power of 13.8 W, indicating that the efficiency of converting pumping optical power to output optical power, η_{opt-opt}, was 49%. The line of the best fit is shown in Fig. 2(b). The slope efficiency η_{slope} was 72% for T = 10%. The maximum output power of 6.8 W was determined to be fourfold higher than 1.7 W and the slope efficiency was determined to be 7% lower than 79% using the 100 μm fiber-coupled LD reported by Dong et al.20 Our 6.8 W laser with the slope efficiency of 72% is expected to have a higher slope efficiency than the present result if the pumping source is replaced with a 100 μm fiber-coupled 25 W LD, for example, LIMO25-F100-DL940 (Lissotschenko Mikrooptick) while maintaining the high output power, because the pumping intensity would increase to a value of fourfold higher than that of a 200 μm fiber-coupled LD. In comparing our laser with the edge-pumped composite Yb:YAG ceramic laser17 developed by Tsunekane and Taira, we limit our discussion to the cw case; the laser power of 414 W obtained by Tsunekane and Taira is much higher than our result, but their slope and optical-optical conversion efficiency were 47 and 44%, which were 25 and 5% lower than our slope and optical-optical conversion efficiency of 72 and 49%, respectively.

This result was obtained after the optimization of the cavity length. The cavity length was varied to obtain an optimum value for the highest efficiency and highest output power, and the focal length of the thermal lens for designing a tunable laser cavity configuration. Figure 3 shows the maximum output power as a function of the cavity length. Figure 3 shows that the optimum cavity length is less than 20 mm. This value is the appropriate cavity length for our laser, because there is no space to reduce the cavity length of less than 20 mm. For information, the optimum cavity length for the highest output power and highest slope efficiency was 25
mm, and reducing the length of less than 25 mm yielded a worse result when we used the 400 μm fiber-coupled LD.\(^\text{19}\) The focal length of the thermal lens in the ceramic Yb:YAG plate was considered for designing a tunable laser cavity configuration. Figure 3 also shows that the focal length of the thermal lens is 109 mm (120 mm (the cavity length) minus 11 mm (the distance of the ceramic Yb:YAG and the DM)), because the cavity becomes unstable, terminating the laser oscillation when the Fabry-Perot cavity length exceeds the thermal lens focal length. By considering this thermal lens, a tunable laser with a v-shape cavity including a concave mirror M (radius of curvature, ROC = 250 mm) and an SF10 dispersive prism was obtained, as shown in Fig. 1. The SF10 dispersive prism is inserted into the V-shape resonator as the tuning element between the folded mirror M and the output coupler OC at Brewster’s angle. The cavity length is 315 mm. Figure 4 shows the dependence of the output power versus the laser oscillation wavelength for the output couplers of \(T = 0.1, 1, 5,\) and 10%, when an absorbed pump power was 13.8 W. There are two separate steep peaks (1031.7 and 1049.0 nm) for \(T = 10\)% and there is no oscillation wavelengths from 1037 to 1048 nm, indicating the loss in the resonator overcomes the relatively small gain of the Yb:YAG ceramics in the region. The tunable ranges from 1022.2 to 1036.8 nm and from 1048.6 to 1051.2 nm with a maximum output power of 5.23 W for \(T = 10\)% were obtained. This tendency is also observed in the case of \(T = 5\)% for the same reason. There are two peaks, but these are continuously connected with a small dip between them. The tunable range was 41.1 nm from 1020.1 to 1061.2 nm with a maximum output power of 4.14 W for \(T = 5\)%.

In the cases of \(T = 1\) and 0.1%, the tuning curves are continuous, smooth and flat, which is due to the small cavity loss, though a gain is relatively small in the spectral region from 1037 to 1048 nm. The tunable range was 63.3 nm from 1027.4 to 1090.7 nm with a maximum output power of 0.12 W for \(T = 0.1\)%.

We achieved a quasi-continuous and smooth tuning range of 63.5 nm, from 1020.1 to 1083.6 nm, with a maximum output power of 1.61 W near 1050 nm for \(T = 1\)%.

To the best of our knowledge, this is the first study of the tunability of an Yb:YAG ceramic laser. The shortest wavelength of the tuning range in Fig. 4 is limited to the dichroic coating range of the pumping mirror (high-reflection coating from 1020 to 1200 nm, Layertec, No. 103542). This 63.5 nm tuning range of the Yb:YAG ceramic laser at 20°C or 293 K is 1.76-fold broader than the 36.0 nm tuning range, from 1018 to 1054 nm, which was produced from the Yb:YAG crystal laser.\(^\text{21}\) Furthermore, our tuning range of 63.5 nm from 1020.1 to 1083.6 nm with the high-power ceramic Yb:YAG laser at 20°C is broader than that of a low-power crystal Yb:YAG laser by Saikawa et al.,\(^\text{22}\) which has the tuning range of 59 nm from 1022 to 1081 nm at 18°C. The widely tunable Yb:YAG crystal laser with birefringent filters reported by Saikawa et al.\(^\text{23}\) had the tuning range of 84.5 nm from 1024.1 to 1108.6 nm; however, the highest output power was 180 mW, which is much lower than the maximum output power of 1.6 W in our ceramic laser with an SF10 prism in Fig. 4. By comparing the output powers of the cases with and without a dispersive tuning element, the maximum output power of the laser was determined to be 1.6 W in Fig. 4 and 6.8 W in Fig. 2. The decrease in laser efficiency is due to the insertion loss of the prism and the mode-volume loss of the long cavity configuration, which can be improved by optimizing the resonator design.

4. Summary

A diode-end-pumped high-efficiency high-power Yb:YAG ceramic laser was demonstrated at a room temperature of 20°C with an Yb concentration of 9.8 at.%, a gain medium thickness of 1 mm, a pumping power of 13.8 W, an output coupler of \(T = 10\)% and a cavity length of 20 mm. A 6.8 W cw output power was obtained with a slope efficiency of 72%. This is the relatively high efficiency of ceramic Yb:YAG lasers at room temperature. The tunable range of 63.5 nm from 1020.1 to 1083.6 nm for \(T = 1\)% was also obtained at room temperature and the highest output power was 1.6 W. To the best of our knowledge, this is the first study of the tunability of ceramic Yb:YAG lasers, except crystal Yb:YAG studies. This tunability could be very attractive for femtosecond laser applications. The cost of Yb:YAG ceramic laser materials...
could be much lower than that of single crystals because of their high-speed and large-size production, and mass-production, which could be tremendously attractive for industrial applications.

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