Efficient tunable Yb:YAG ceramic laser

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ABSTRACT

A high-power efficient ceramic Yb:YAG laser was demonstrated at a room temperature of 20 °C with a Yb concentration of 9.8 at.%, a gain medium of 1 mm, a pumping power of 13.8 W, an output coupler of T = 1%, 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.

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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; multiplier and multifunctional ceramic laser materials are possible because of the polycrystallinity of ceramics [4]. 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, Ikeue and coworkers have been developing several types of ceramic laser material [1,2], and they found in 2000 that the output power from a 3.4 at.% Nd:YAG ceramic chip laser is twice that from a Nd:YAG crystal microchip laser of the same size [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 (Yb3+) doped materials are very attractive for diode-pumped solid-state lasers (DPSSLs) [8]. The Yb3+-doped materials have high quantum efficiency and exhibit no concentration quenching simply because the Yb3+ ion has only two manifolds, namely, the ground state 2F7/2 and the upper level 2F5/2. 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 exists at the Stark level of the lower manifold 2F7/2, where laser transition terminates, which requires high-intensity pumping, a high-brightness pump source, and an efficient heat removal technique [12–14] 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% [15]. Recently, Tsunekane and Taira have demonstrated a high-power diode-edge-pumped single crystal Yb:YAG/ceramic undoped YAG composite microchip laser [16,17]. Early in 2007, a diode-edge-pumped, composite allceramic 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% [18]. 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% [19]; 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 [20] with a 400 µm fiber-coupled LD. Dong et al. demonstrated a highly efficient (a slope efficiency of 79%) Yb:YAG ceramic laser [21] 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 tunability of Yb:YAG crystal lasers [22–24]. In 2000, the widest tunability range from 1024.1 to 1108.6 nm was demonstrated with a 160 mW Yb:YAG crystal laser using a 0.1% output coupler and a birefringent filter by Saikawa et al. [23]. Subsequently, Saikawa et al. reported a 180 mW Yb:YAG crystal laser with a tunability in the spectral range of 59 nm from 1021.9 to 1081.2 nm in 2002 [24]. In this study, we investigated the tunability of a 1.5 W Yb:YAG ceramic laser using a 1% output coupler and a prism, because the ceramic laser has a low cost, is a large size, and enables rapid mass production. The tunable range of the watt class Yb:YAG ceramic laser was 63.5 nm from 1020.1 to 1083.6 nm.

2. Experimental setup

The experimental setup for the 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 diameter of 1 mm 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 (C9o = 9.8 at.%, Konoshima Chemical) with dimensions of 5 × 10 × 1 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 20 °C during laser oscillation. The cavity length was 20 mm, which was optimized, as shown in the later part of this letter. Fig. 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 [12,13]. Finally, a tunable laser setup with a V-shape cavity including a concave mirror M (radius of curvature, ROC = 250 mm) and an SF10 dispersive prism is 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 was 315 mm.

3. Experimental results

Fig. 2a shows the output power as function of the absorbed pump power in the cases for the three transmittances of the output couplers T = 1, 5, and 10%. Fig. 2b shows the output power as function of the absorbed pump power only for 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. The round trip loss L in the resonator was estimated to be 0.09 by the lasing thresholds and the reflectivity of the output couplers [25], which resulted in a small signal gain g0 of 2.0 cm−1, and a single pass gain G of 1.2 with the 1 mm thick gain medium. Each line was fit in Fig. 2a for T = 1, 5, and 10%. The slope efficiencies ηslope 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. 2b. 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, ηslope-opt, was 49%. The line of the best fit is shown in Fig. 2b. The slope efficiency ηslope was 72% for T = 10%. The maximum output power of 6.8 W was determined to be fourfold higher than that of a 200 µm fiber-coupled LD reported by Dong et al. [21]. 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, LMO25-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 laser [18] 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. The
The transverse intensity profile of the Yb:YAG ceramic laser beam is shown in Fig. 3. The intensity distribution indicates that the beam is a Gaussian beam (a TEM\(_{00}\) mode beam). The beam image in Fig. 3 was as stable as the pumping LD and we found no amplitude instability.

These results of high output power, high efficiency, and good beam quality were 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. Fig. 4 shows the maximum output power as a function of the cavity length. Fig. 4 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 less than 20 mm. When we used the 400 \(\mu\)m fiber-coupled LD [20], the optimum cavity length with the highest output power and highest slope efficiency was 25 mm, and reducing the length less than 25 mm yielded a worse result.

The focal length of the thermal lens in the ceramic Yb:YAG plate was considered for designing a tunable laser cavity configuration.

Fig. 4 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. Fig. 5 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 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 for \(T = 1\%\). The tunable ranges from 1022 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 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. 5 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 with a three-plate birefringent filter at 218 and 248 K [22]. 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 ceramic Yb:YAG laser by Saikawa et al. [23], 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. [24] 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. 5. 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. 5 and 6.8 W in Fig. 2. The decrease in laser output power is due to the insertion loss of the prism and the mode-volume mismatch loss between pump beam and laser beam in the 315 mm long cavity configuration with the arm including prism, comparing the linear 20 mm short cavity laser used to measure the output power in Fig. 2, which can be improved by optimizing the resonator design. For example, the laser beam waist comes to the place of the ceramic Yb:YAG even using a long cavity when the resonator type is improved from the V-shape cavity to a symmetric Z-shape or X-shape cavity.

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 beam quality was shown as a transverse intensity distribution indicating a Gaussian beam (a TEM00 mode beam). 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 and suitable for a laser amplifier (the maximum single pass gain of 1.2 with the gain medium of 1 mm thickness). 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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