Continuous-wave and *Q*-switched performance of an Yb:YAG/YAG composite thin disk ceramic laser pumped with 970-nm laser diode

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Using front face-pumped compact active mirror laser (CAMIL) structure, we have demonstrated an Yb:YAG/YAG composite ceramic disk laser with pumping wavelength at 970 nm. The laser has been operated in both continuous-wave (CW) and *Q*-switching modes. Under CW operation, laser output power of 1.05 W with 2% transmission output coupler was achieved at the wavelength of 1031 nm. *Q*-switched laser output was gotten by using an acousto-optic *Q*-switch. The repetition rate ranged from 1 to 30 kHz and the pulse width varied from 166 to 700 ns.

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Novel nanotechnology has made it possible to synthesize highly homogeneous transparent laser ceramic whose profile and structure can be designed freely before sintering. These kinds of composite ceramic can solve many different problems that traditional media cannot do, such as realizing spectrum emerging[1], suppressing amplified spontaneous emission (ASE) in the medium[2], compensation for the thermal stress and distortion[3], and so on. Besides, this new kind of material (polycrystal ceramic) is superior to single crystal in many aspects, such as improved thermo-mechanical properties, multifunctional "all-in-one" ceramic, faster and cheaper for mass production[4]. Many progresses have been reported on the Nd:YAG/YAG ceramic lasers[1,5−10].

Benefitting from the high quantum efficiency of over 90% and longer upper-state lifetime of ∼ 1 ms, Yb:YAG has been an attractive choice for high-power output. Moreover, the simple two-level electronic energy structure of Yb in YAG allows for no excited state absorption, no up-conversion, and minimal concentration quenching. Diode lasers operating at 941 or 970 nm can be used as pump sources for efficient absorption. The thin disk geometry has been shown to be highly effective for Yb:YAG and has become popular and successful in recent years[11,12]. Compared with rod shape medium in which the heat distribution is along the radius of the rod and so there is strong thermal gradient induced lensing and birefringence, the heat distribution in a thin disk shaped gain medium is extracted through the large faces with thermal gradients, which is established across the smallest dimension and aligned with the beam propagation direction[13]. In China, there has been no relevant report on this kind of composite ceramic thin disk laser so far.

An Yb:YAG/YAG composite thin disk ceramic laser pumped with 970-nm laser diodes (LDs) is presented in this letter. We have demonstrated the disk laser in both continuous-wave (CW) and *Q*-switching operation with face-pumped compact active mirror laser (CAMIL) structure. In the CW mode, we got a maximal output power of 1.05 W at 1031 nm. In the *Q*-switching mode, the minimal pulse width of 166 ns and the maximal average output power of 0.47 W were achieved, and the repetition rate ranged from 1 to 30 kHz.

In order to increase the effective absorbing length in the thin-disk medium and make a good overlap between pump and resonator modes, a face-pumped CAMIL structure was chosen. With this structure, diode pump radiation was injected into the back surface of the disk and then reflected by the surfaces several times. The diagram of the experimental setup is shown in Fig. 1. The laser medium is a composite Yb:YAG/YAG thin disk ceramic in which the very thin absorbing part of the disk (0.6 mm) is bonded together with an undoped piece of YAG ceramic (2.5 mm). The doping concentration was 9.8 at.-% in the doped part. The composite ceramic disk was anti-reflection (AR) coated for the wavelengths of the pump 970 nm and laser radiation 1030 nm at the front side and high-reflection (HR) coated for both wavelengths at the back side. It was fixed with a layer of indium onto a heat sink, which was cooled with water

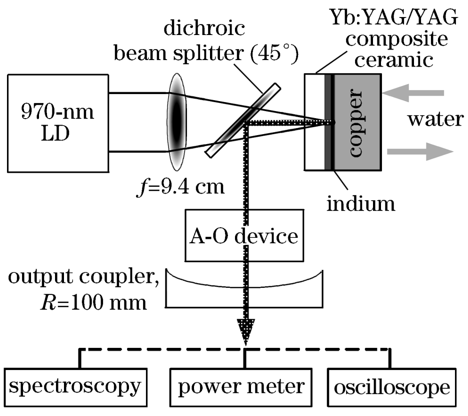

Fig. 1. Schematic diagram of the experimental setup.

from the back side. A collimated LD array with central wavelength at 970 nm working at 15 °C was used as the pump source. By an f = 9.4 cm lens, the pumping light was focused on the back side of the ceramic and the unabsorbed pumping radiation was reflected for another turn of absorption, i.e, the effective absorbing length was twice the length of the doped ceramic. A dichroic beam splitter (45°) which was coated with AR film at 970 nm and HR film at 1030 nm was located between the focusing lens and the composite ceramic. It was used for redirecting the laser to the output couplers. In the CW mode, output couplers with transmissions of 1%, 2%, 5%, and 10% were used respectively, with the radius of curvature of 100 mm. The whole cavity length was about 80 mm. In the Q-switching mode, output coupler with transmission of 10% was used. The output laser power was measured by a powermeter (NOVA II, OPHIR, Israel) and the spectrum was recorded by an optical spectrum analyzer (OSA) (Yokogawa, AQ6370, Japan), while the pulse width was recorded by an oscilloscope (WR62XR, LeCroy, USA).

In the CW mode, the laser output power increases as the pump power increases with different output couplers, as shown in Fig. 2. Up to 1.05 W CW power with 2% output coupler, the optical-to-optical efficiency was 5.25%. Central wavelength was at 1031 nm, as shown in Fig. 3. We also got Q-switched laser output using an acousto-optic (A-O) Q-switch. The A-O Q-switch (M080-2G, Gooch and Housego, UK) was inserted into the cavity with 10% transmission output coupler. Stable operation was achieved with the repetition rates of 1, 5, 10, 20, and 30 kHz, corresponding to the average output powers of 0.44, 0.446, 0.452, 0.461, and 0.47 W, respectively. The pulse width was enlarged with the increasing repetition rate, as shown in Fig. 4. The pulse waveform at 1 kHz is shown in Fig. 5, from which we can see a minimal pulse width of 166 ns and the corresponding peak power is 2.6 kW. The pulse train is shown too, which appears to be a bit unstable but acceptable.

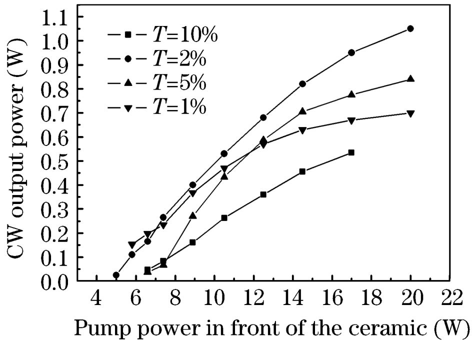

Fig. 2. CW laser output power versus pump power with different output transmissions.

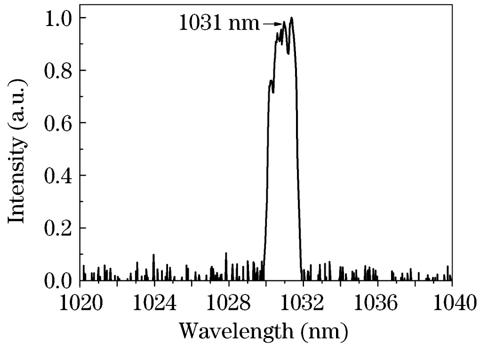

Fig. 3. Laser spectrum.

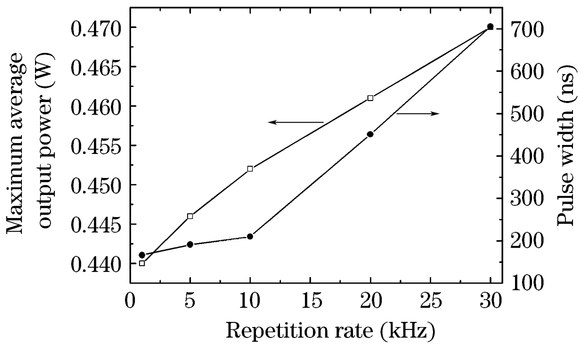

Fig. 4. Average output power and pulse width versus repetition rate.

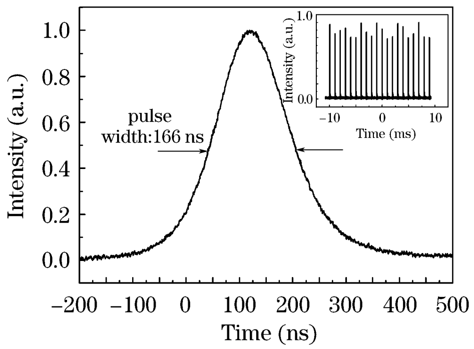

Fig. 5. Pulse profile of minimum pulse width at 1 kHz. Inset shows the pulse serial.

For both CW and AO Q-switching modes, the optical-to-optical efficiency is low according to the data in Figs. 2 and 4. But when we consider the actual absorbed pump power, the case will be different. Figure 6 shows the double-pass absorptivity of the disk ceramic. There was only 53.5% of the pump power absorbed at the pump wavelength 970 nm. We measured the relationship between pump wavelength and pump power while maintaining the temperature of the cooling water at 15 °C. We found that the pumping wavelength drifted dramatically along with the increasing pump power, from 970 to 979 nm, as shown in Fig. 7. It means that even less

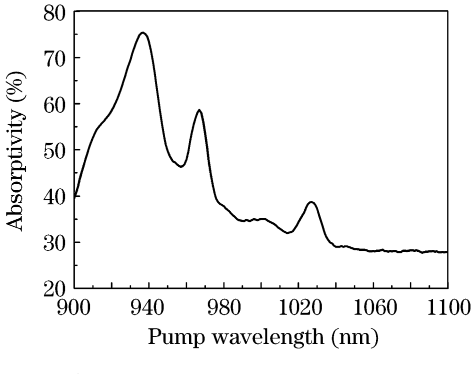

Fig. 6. Absorptivity of the composite ceramic.

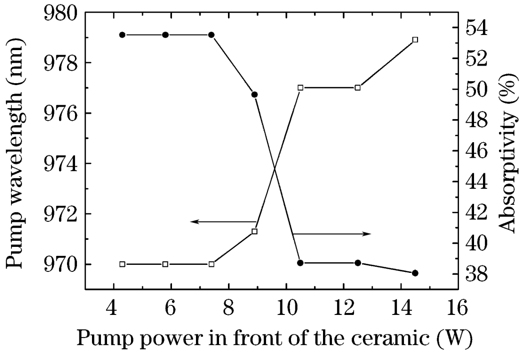

Fig. 7. Pump wavelength drifting with pump power and the corresponding absorptivity.

pump power was absorbed when the pumping power increased, varying from 53.5% at 970 nm to 38% at 979 nm (see Fig. 6). In higher pump power region, the laser power tended to be “saturable”, as shown in Fig. 2, which is caused by the decreasing absorption efficiency of the medium. In this experiment, we found that it was difficult to control the pump wavelength only by cooling in this pump source. Figure 6 indicates that the increased absorbing length brings about 28% background absorption of the pump power, which might be caused by the quality of the media. It would raise the laser threshold. It is also shown in Fig. 6 that there is another absorption peak at around 1031 nm which is exactly the output laser wavelength, indicating the reabsorption at 1031 nm. Thus, the increasing pumping power would lead to a stronger reabsorption, resulting in a quick saturation at this wavelength. Moreover, the unabsorbed pump energy would contribute to the difficulty of the population inversion and lead to the thermal lensing effect, which would further reduce the efficiency and the laser output power.

In summary, we demonstrated a CW and *Q*-switched laser with composite Yb:YAG/YAG ceramic pumped by 970-nm LD. A maximum laser power of 1.05 W with central wavelength at 1031 nm was obtained. A minimal pulse width of 166 ns and the maximal peak power of 2.6 kW at 1 kHz were achieved, correspondingly, the average output power was 0.44 W. The repetition rate ranged from 1 to 30 kHz. By analyzing the absorptivity of the media and the drifting of pumping wavelength, we gave reasonable explanation for our results. The next step is to use another pump source with precise and stable central wavelength at 970 nm to explore the full advantages of 970-nm pumping Yb:YAG/YAG.

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References

1. T. Taira, IEEE J. Sel. Top. Quantum Electron. **13,** 798 (2007).
2. A. Heller, “Transparent ceramics spark laser advances” https://www.llnl.gov/str/april06/soules.htm (April 15, 2008).
3. H. Yu and G. Bourdet, Appl. Opt. **44,** 7161 (2005).
4. K. Ueda, J.-F. Bisson, H. Yagi, K. Takaichi, A. Shirakawa, T. Yanagitani, and A. A. Kaminskii, Laser Phys. **15,** 927 (2005).
5. “Solid-state heat-capacity laser” https://lasers.llnl.gov/programs/psa/directed_energy/sshcl.php (April 15, 2008).
6. D. Kracht, D. Freiburg, R. Wilhelm, M. Frede, and C. Fallnich, Opt. Express **14,** 2690 (2006).
7. Y. Qi, Q. Lou, H. Ma, and J. Dong, Chin. Opt. Lett. **3,** 89 (2005).
8. J. Ji, X. Zhu, C. Wang, Y. Feng, and Q. Lou, Chin. Opt. Lett. **4,** 219 (2006).
9. J. Li, B. Jiang, Y. Pan, Y. Wu, J. Li, J. Xu, X. Feng, L. Huang, and J. Guo, Chinese J. Lasers (in Chinese) **33,** 864 (2006).
10. J. Ji, Y. Qi, X. Zhu, and Q. Lou, Acta Opt. Sin. (in Chinese) **26,** 415 (2006).
11. U. Brauch, A. Giesen, M. Karszewski, C. Stewen, and A. Voss, Opt. Lett. **20,** 713 (1995).
12. M. Tsunekane and T. Taira, Opt. Lett. **31,** 2003 (2006).
13. A. Giesen, Laser Technik Journal **2,** (2) 42 (2005).