Highly efficient Nd:YAG ceramic CW laser with 59.8% slope-efficiency

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In this paper, a highly efficient Ti:sapphire end-pumped 1 at.-% Nd:YAG ceramic laser that is comparable in efficiency with Nd:YAG single crystal lasers has been developed. Optical absorption and emission spectra for Nd:YAG ceramics have been measured. With 673-mW pumping, 295-mW laser output at 1064 nm has been obtained. The laser threshold is only 13 mW. Deducted the transmitted light, the corresponding optical-to-optical conversion efficiency is 58.4%. The lasing characteristics of Nd:YAG ceramic are nearly equal to those of Nd:YAG single crystal.

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Since Maiman discovered the ruby laser in 1960, the solid state lasers have been rapidly developed and applied in various fields. In all solid state lasers, Nd:YAG single crystals play the most important role. But it is very difficult to fabricated YAG single crystals doped with > 1 at.-% elemental neodymium by Czochiralki method[1,2], because the effective segregation coefficient of elemental neodymium for the host material is quite low (~ 0.2). Recently, Nd:YAG ceramic laser materials have attracted much attention. Since the quality of Nd:YAG ceramics has been improved greatly and highly efficient laser oscillations could be obtained, the ceramics are becoming strong challenger to single crystals. Compared with single crystals, transparent ceramics have several advantages, easily fabricating, low cost, large size and high doping concentration, multi-layer and multi-functional structure, and mass production, etc.. These advantages give much more flexibility in laser design[3,4].

Early in 1966, hot-pressed CaF_2 doped with dysprosium appeared to be the first report polycrystalline material which established laser oscillation[5]. But several decades passed, no breakthrough had been achieved because the scattering losses of ceramic hosts were too high to achieve effective laser output. Until 1995, Ikesue *et al.* fabricated highly transparent Nd:YAG ceramics. The scattering losses (0.009 cm^{-1}) for these samples were low enough to obtain laser output for the very first time[6]. In 1999, Yanagitani *et al.* developed Nd:YAG ceramics successfully by a modified urea precipitation method[7,8]. They prepared fine YAG particles of around 10 nm in diameter in the combination of liquid phase chemical reaction and pre-sintering technique. The ceramic formation process and sintering process have been optimized for fabricating highly transparent Nd:YAG ceramics. The average diameter of grain size is about 10 μm with grain boundary width less than 1 nm, such a narrow grain boundary and very low pore volume ensure very low scattering loss inside the ceramic samples. In Refs. [9, 10], the experimental results indicated a highly efficient CW Nd:YAG ceramics laser output with an oscillation threshold of 20 mW and a slope efficiency of 60.9%. And in Ref. [11], high power CW laser oscillation with Nd:YAG ceramics rod using virtual point source (VPS) pumping system was demonstrated. With 290-W pumping, 72-W laser output at 1064 nm has been obtained.

Optical absorption, emission spectra for Nd:YAG ceramics have been measured and compared to those of single crystal, very similar results were obtained.

The room temperature absorption spectra of 1 at.-% Nd:YAG ceramics and 1.1 at.-% Nd:YAG single crystals are shown in Fig. 1. From it, we can find that the two spectra are almost identical except that the absorption intensity of 1 at.-% ceramic is a little difference with that of 1.1 at.-% single crystal because of the different neodymium concentration in these two samples. The main absorption peak of 1 at.-% ceramic is centered at 808 nm which is similar to that of single crystal.

Figure 2 shows the room temperature emission spectra for 1 at.-% Nd:YAG ceramic and 1.1 at.-% Nd:YAG

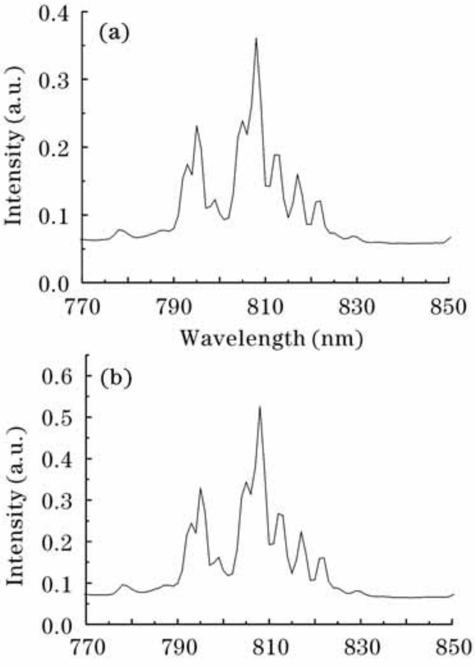

Fig. 1. Absorption spectra for (a) 1 at.-% ceramic and (b) 1.1 at.-% single crystal between 770 and 850 nm.

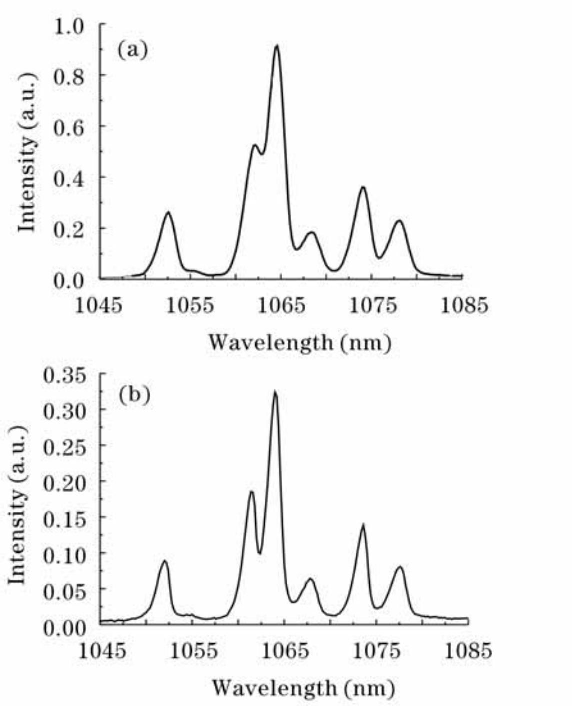

Fig. 2. Emission spectra of (a) 1 at.-% ceramic and (b) 1.1 at.-% single crystal excited by Ti:sapphire laser of 808 nm.

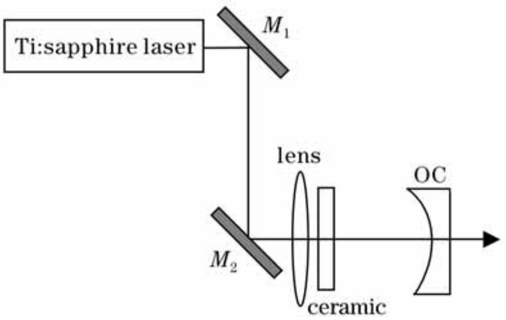

Fig. 3. Schematic diagram of the laser experimental setup.

single crystal, respectively. Also, except the intensity, the two spectra are almost identical. The emission peak of 1 at.-% ceramic is centered at 1064 nm, the same as that of 1.1 at.-% single crystal.

The laser experimental setup is shown in Fig. 3. 1 at.-% Nd:YAG ceramic laser was demonstrated by using Ti:sapphire end-pumped scheme. An 808-nm pump light of Ti:sapphire laser is focused to a > 50 μm spot radius inside the ceramic with a 75-mm focal length lens. The 1.2-mm-thick 1 at.-% Nd:YAG ceramic is coated with HR 1064-nm/AR 808-nm films to act as a cavity mirror of the laser on one end , the other end is antireflection coated at 1064 nm to reduce the cavity losses. In all measurements we use a concave mirror as output coupler (OC) with 50-mm radius and the reflectivity is 95% at 1064 nm. The cavity length is about 47 mm. A 1-mm-thick 1.1 at.-% Nd:YAG single crystal sample is used for comparison. The coating is the same as that of ceramic sample.

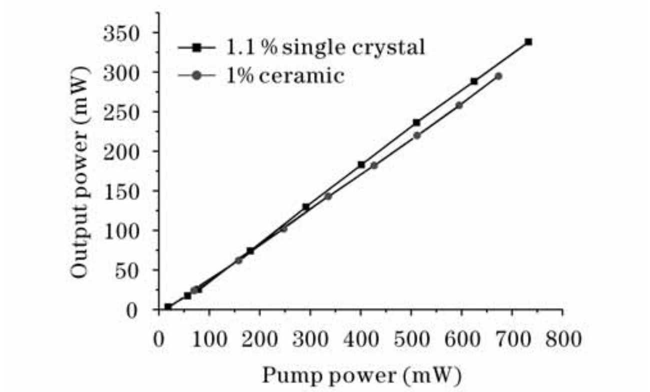

Fig. 4. Laser output at 1064 nm versus pump power.

Figure 4 shows the laser output versus pump power for the 1 at.-% Nd:YAG ceramic laser and 1.1 at.-% Nd:YAG single crystal, respectively. The threshold for 1 at.-% ceramic is 13 mW which is very close to that of single crystal (12 mW). The slope efficiencies are 45% and 47% for the ceramic laser and the single crystal laser, respectively. The corresponding optical-to-optical conversion efficiency is 44% for ceramic laser, and 46% for single crystal laser. The thresholds and slope efficiencies show that these two kinds of laser materials share extraordinary laser output properties.

Because the ceramic sample and single crystal sample have different doping concentrations and thicknesses, the absorbed pump power rather than incident pump power is more reasonable here, which means transmitted light has been deducted. So we use absorbed power to calculate efficiencies and get a new result. As show in Table 1, The slope efficiency is 59.8% and the corresponding optical-to-optical conversion efficiency is 58.4% for our 1 at.-% Nd:YAG ceramic laser. These results are very close to the best data reported in Ref. [9] (slope efficiency = 60.9%, O-O efficiency = 59.4%). No saturation appeared in our experiment, the output power would increase with increasing the pump power.

In conclusion, a new and highly efficient ceramic laser was demonstrated to have the same efficiency with Nd:YAG single crystal lasers. The laser performance of Nd:YAG ceramics exited with an 808-nm laser is affected greatly by the optical scattering losses, and the performance can be improved by decreasing losses. Being able to fabricate large size (now about $\phi 450\times 10$ mm sample is available) and high concentration (up to s neodymium concentration of 4.8 at.-%), Nd:YAG ceramic lasers offer design flexibility and pricing options. They are very good alternative to Nd:YAG single crystals. These still-evolving ceramic lasers have the potential to dramatically reshape today's marketplace for solid state lasers.

Table 1. Laser Parameters Calculated According to Absorbed Pump Power

	Absorbed Power	Output Power	O-O Efficiency	Threshold	Slope Efficiency
1 at.-% ceramic	505 mW	295 mW	58.4%	13 mW	59.8%

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References

1. K. Shiroki and Y. Kuwano, Nippon Kagaku Kaishi **7,** 940 (1978).
2. R. R. Monchamp, J. Cryst. Growth. **11,** 310 (1971).
3. J. Lu, M. Prabhu, K. Ueda, H. Yagi, T. Yanagitani, A. Kudryashov, and A. A. Kaminskii, Laser Physics **11,** 1053 (2001).
4. J. Lu, K. Ueda, H. Yagi, T. Yanagitani, Y. Akiyama, and A. A. Kaminskii, J. Alloys and Compounds **341,** 220 (2002).
5. E. Carnell, S. E. Hatch, and W. F. Parson, *Materials Science Research* (Plenum, New York, 1966) p.165.
6. A. Ikesue, Y. Kinoshita, K. Kamata, and K. Yoshida, J. Am. Ceram. Soc. **78,** 1033 (1995).
7. T. Yanagitani, H. Yagi, and A. Ichikawa, "Production of yttrium-aluminum-garnet fine powder" Japanese patent 10-101333 (1998).
8. T. Yanagitani, H. Yagi, and H. Yamazaki, "Production of fine powder of yttrium aluminum garnet" Japanese patent 10-101411 (1998).
9. J. Lu, M. Prabhu, J. Xu, K. Veda, H. Yagi, T. Yanagitani, and A. A. Kaminskii, Appl. Phys. Lett. **77,** 3707 (2000).
10. J. Lu, T. Murai, K. Takaichi, T. Uematsu, M. Prabhu, K. Veda, H. Yagi, T. Yanagitani, and A. A. Kaminskii, Advanced Solid-State Lasers **50,** 610 (2001).
11. J. Lu, T. Murai, K. Takaichi, T. Uematsu, K. Misawa, M. Prabhu, J. Xu, K. Ueda, H. Yagi, T. Yanagitani, A. A. Kaminskii, and A. Kudryashov, Appl. Phys. Lett. **78,** 3586 (2001)