Highly efficient 2% Nd:yttrium aluminum garnet ceramic laser

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A highly efficient diode-laser end-pumped polycrystalline 2% Nd:yttrium aluminum garnet (YAG) ceramics laser that is comparable in efficiency with Nd:YAG single crystal laser has been developed. With 883 mW pumping, 465-mW-cw laser output at 1064 nm has been obtained corresponding to an optical-to-optical efficiency of 52.7%. The laser threshold is only 30 mW with $R=97\%$ output coupler. © *2000 American Institute of Physics.* [S0003-6951(00)02250-6]

Nd-doped yttrium aluminum garnet (YAG) single crystal fabricated by the Czochralski method has been widely used as solid-state laser material but it is extremely difficult to dope $>1\%$ neodymium homogeneously as a luminescence element in a YAG single crystal because the effective segregation coefficient of elemental neodymium is only ~ 0.2. Compared to single growth method, the ceramics fabrication process can give us high neodymium concentration[1] and large size (now $\phi 450$ mm$\times$10 mm sample is available) polycrystalline Nd:YAG ceramics. No special technique nor expensive Ir crucible is required. In the last decade, investigations have been made to obtain high quality, highly transparent Nd-doped YAG ceramics that can be used as a laser material to compete with Nd:YAG single crystal. In 1995, Ikesue *et al.* fabricated highly transparent Nd:YAG ceramics. Some physical properties of Nd:YAG ceramics, such as refractive index, thermal conductivity, etc. were measured and compared to that of Nd:YAG single crystal. Very similar results were obtained.[2] The scattering loss ($0.009\ \mathrm{cm}^{-1}$) for this sample was sufficiently low to obtain laser oscillation. A slope efficiency of 28% was reported.

Recently, Konoshima Chemical Co. Ltd. developed Nd:YAG ceramics by a different method.[3,4] The ceramics formation process and sintering process were optimized and highly transparent, high quality Nd:YAG ceramics were fabricated. The average diameter of grain size is about 10 μm. The grain boundary width is below 1 nm. The porosity in this kind of ceramics is only 1 ppm level.

This letter describes a diode-pumped highly efficient 2% Nd:YAG ceramics laser at 1064 nm. The threshold and slope efficiency are almost the same level with that of 0.9% Nd:YAG single crystal laser.

The room temperature absorption spectrum of 2% Nd:YAG ceramic is shown in Fig. 1. The absorption spectrum of a 0.9% Nd:YAG single crystal (procured from Litton-Airtron Inc.) is also shown in Fig. 1 for comparison. From this figure, we see that the peak absorption coefficient of 2% Nd:YAG ceramics ($20.8\ \mathrm{cm}^{-1}$) is about 2.3 times larger than that of 0.9% Nd:YAG single crystal ($9.2\ \mathrm{cm}^{-1}$). The main absorption peak of 2% ceramics is centered at 808.56 nm which is slightly red shifted compared to that of single crystal (808.48 nm) because of a slight change in the crystal field in the high neodymium concentration samples.

Figure 2 shows the room temperature fluorescence spectra for 2% Nd:YAG ceramic and 0.9% Nd:YAG single crystal, respectively. For comparison, the fluorescence spectrum for single crystal and ceramic are normalized and put together. A slight redshift was also observed in emission spectrum because of high neodymium concentration. The emission peak of 2% Nd:YAG ceramic is centered at 1064.2 nm which is 0.1 nm redshifted away from that of 0.9% Nd:YAG single crystal. Except the slight redshift, the two spectra are almost identical to each other.

The laser experimental setup for a 2% Nd:YAG ceramic laser is shown in Fig. 3. A 1 W high brightness Hamamatsu 2901 laser diode (LD) with $1\times50\ \mu\mathrm{m}^2$ emission profiles is

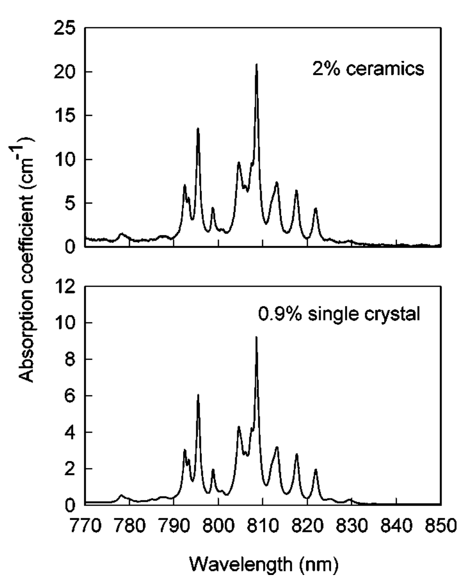

FIG. 1. Absorption spectrum from 770 to 850 nm.

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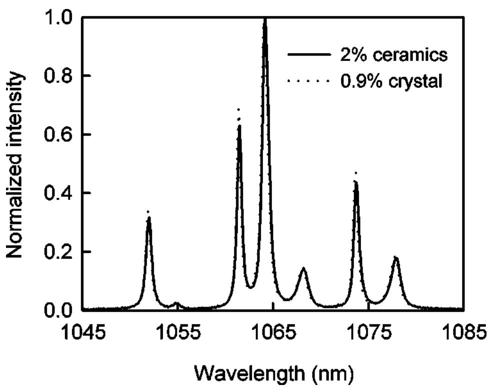

FIG. 2. Fluorescence spectrum from 1045 to 1085 nm.

used as a pump source. The light from the diode laser is collimated and focused by a pair of 8 mm focal length lenses. When the LD output is 1 W, about 883 mW pump power can be focused on the end of sample. The 2.5 mm thick 2% Nd:YAG ceramic is coated with HR1064 nm/AR808 nm films to act as a cavity mirror of the laser on one end, the other end was antireflection coated at 1064 nm to reduce the cavity loss. Output mirror is a concave mirror with 250 mm radius and the reflectivity is 97% at 1064 nm. The cavity length is about 20 mm. A 5 mm thick 0.9% Nd:YAG single crystal sample procured from Litton-Airtron Inc. was used for comparison. The thickness and coatings are the same with that of ceramic sample.

Figure 4 shows the laser output versus input power for the 2% Nd:YAG ceramic laser and 0.9% Nd:YAG single crystal, respectively. The thresholds for 2% Nd:YAG ceramic is 30 mW which is a little larger than that of single crystal (22 mW). The slope efficiencies are 55.4% and 55.2% for the ceramic laser and single crystal laser, respectively. With 883 mW maximum pump power, 465 and 474 mW laser output were obtained at 1064 nm for the ceramic laser and single crystal lasers, respectively. The corresponding optical-to-optical conversion efficiency is 52.7% for the ceramic laser and 53.7% for single crystal laser.

Because the ceramic sample shares different neodymium concentration and sample thickness with single crystal, under the same maximum pump power of 883, 842, and 795 mW pump power were absorbed by the 2.5 mm 2% ceramic and 5 mm 0.9% single crystal, respectively. To have a reasonable comparison, absorbed pump power should be used to calculate the efficiencies. Table I lists all results calculated according to absorbed pump power for ceramic and single crystal, respectively.

The threshold of the 2% ceramic laser (27 mW) is still a little larger than that of the single crystal laser (20 mW). The slope efficiency is 57.6% which is only 3% less than that of the 0.9% single crystal laser. The thresholds and slope efficiencies show that these two kinds of laser materials share very similar laser output properties.

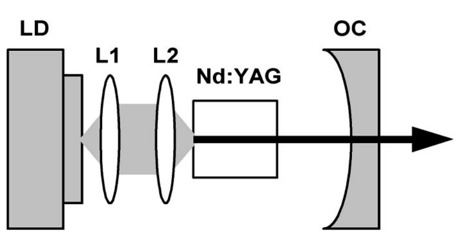

FIG. 3. Schematic diagram of the laser experimental setup. LD: laser diode; L1, L2: collimating and focusing lens; OC: output coupler.

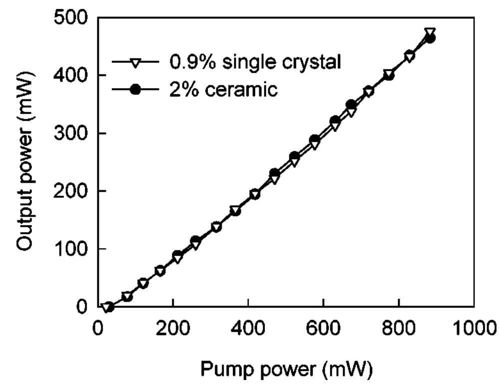

FIG. 4. Laser output at 1064 nm vs pump power.

The fluorescence lifetimes for the 0.9% single crystal and the 2% Nd:YAG ceramic are 248.6 and 184.2 μs, respectively (measured by a quasi-cw LD). The difference in lifetimes indicates the occurrence of concentration quenching and also large neodymium concentration causes reduction in crystal field symmetry. Because of quenching effect and crystal field symmetry reduction, the laser gain for high concentration ceramics should be lower than that of low concentration single crystal but the absorption coefficient increases almost linearly with increasing the neodymium concentration. The optimum thickness for laser materials is reduced because of high absorption coefficient. In a round-trip, the laser beam travels shorter distance inside thin laser media that make it experience less scattering loss inside laser media. Additionally, since the LD output beam has large divergence angle, thin laser materials have better mode match between the pump beam and laser oscillation mode.

During the ceramic sintering process (for a period of about 5 h), the raw powder materials (about 300 nm in dimension) grow into small crystal grains with diameter of about 10 μm. Additionally, a small amount of SiO_2 is doped into Nd:YAG ceramics to aid in sintering process. Such extremely slow grain growth speed and doped SiO_2 sintering aid ensure that the neodymium ions have a good replacement of yttrium ions with less lattice distortion, strains and inclusions inside grains when compared to single crystal growth method.[5] Such advantages listed above resulted in a highly efficient 2% Nd:YAG ceramic laser that is very similar in efficiency with that of 0.9% Nd:YAG single crystal.

Structural differences between single crystal and the polycrystalline ceramics result in the existence of grain boundary and pores. The relationship between the scattering loss and grain boundary dimension and porosity were measured previously.[6,7] In order to reduce the scattering loss in

TABLE I. Laser parameters calculated according to absorbed power.

	Absorbed power (mW)	Output power (mW)	Threshold (mW)	Slope efficiency (%)
Ceramics	842	465	27	57.6
Single crystal	795	474	20	60.6

ceramics, the grain boundary width and porosity should be as small as possible. In the ceramics used in this work, the grain boundary width is less than 1 nm, which is three orders of magnitude less than the laser wavelength of 1064 nm. According to Rayleigh scattering theory, it can be predicted that the size of scattering center near Nd:YAG ceramics grain boundaries is sufficiently smaller than 1 μm, so although the lasing light in laser cavity travels tens of thousand times through grain boundaries, the total scattering loss caused by the grain boundaries is still very low. The porosity in our ceramics is only 1 ppm which is much less than the previous report.[6] The laser experimental results mean the scattering loss in ceramics is close to that of single crystal ($0.002\ cm^{-1}$) at 1064 nm wavelength. The scattering loss of ceramics laser materials will be investigated in more detail later.

One of the advantages of high concentration Nd:YAG is that it can be used in microchip lasers to generate single frequency output efficiently. Since Nd:YAG has much better thermomechanical properties than Nd:YVO_4, high concentration Nd:YAG is a very good alternative in single frequency lasers. Developing highly efficient single frequency Nd:YAG ceramic lasers is our next step.

In conclusion, a highly efficient 2% Nd:YAG ceramic laser was demonstrated to have the same level in efficiency with a Nd:YAG single crystal laser. Apart from having the same level of lasing efficiencies, fabrication of large size high concentration Nd:YAG ceramics is much easier compared to the single crystal growth method. Nd:YAG ceramic laser material is a very good alternative to Nd:YAG single crystal.

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[1] A. Ikesue, J. Am. Ceram. Soc. **79**, 1921 (1996).
[2] A. Ikesue, T. Kinoshita, K. Kamata, and K. Yoshida, J. Am. Ceram. Soc. **78**, 1033 (1995).
[3] T. Yanagitani, H. Yagi, and M. Ichikawa, Japanese Patent No. 10-101333 (1998).
[4] T. Yanagitani, H. Yagi, and Y. Hiro, Japanese Patent No. 10-101411 (1998).
[5] A. Ikesue and K. Kamata, J. Ceram. Soc. Jpn. **103**, 489 (1995).
[6] A. Ikesue, K. Yoshida, T. Yamamoto, and I. Yamaga, J. Am. Ceram. Soc. **80**, 1517 (1997).
[7] A. Ikesue and K. Yoshida, J. Mater. Sci. **34**, 1189 (1999).