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110 W ceramic Nd^{3+} : $Y_3Al_5O_{12}$ laser

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ABSTRACT A high-power, continuous-wave 0.6% Nd^{3+}-doped ceramic $Y_3Al_5O_{12}$ (Nd : YAG) laser has been developed. 110 W laser output at 1064 nm was obtained, with a slope efficiency of about 41%. The M^2 factor was found to be around 6. The laser performance of the ceramic laser material was found to compare favorably with that obtained with single crystal Nd : YAG.

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1 Introduction

The recent development of Nd^{3+}-doped ceramic $Y_3Al_5O_{12}$ (Nd : YAG) laser material using nanocrystalline technology and the vacuum sintering method (NTVS) is probably the most important innovation in the field of laser material fabrication technology in the last decade [1–3]. Such ceramic technology exhibits several key advantages over conventional single crystal growth technologies. For instance, the possibility of growing large samples at low cost and at an improved production rate opens the door to mass production of this material. On the other hand, the possibility of increasing the neodymium doping concentration (greater than 4%at. is possible) compared to melt-grown technologies makes it possible to miniaturize the laser materials and points the way to new applications, such as single-mode microchip lasers. Moreover, by enabling the fabrication of multi-layer components, the ceramic technology makes it possible to obtain multifunctional structures in a single, monolithic constituent.

The obvious advantages of ceramic laser fabrication technologies were recognized a long time ago. Hot-pressed CaF_2 doped with dysprosium appears to be the first reported ceramic laser material, which established laser oscillation in 1966 [4], but the optical quality of such samples were poor. More recently, ceramic Nd : YAG with higher transparency were fabricated, and laser oscillation was reported by Ikesue et al. in 1995 with a slope efficiency of 28% [5]. Still, scattering losses at grain boundaries and residual pores prevented lasing performance approaching those of single crystals. Nevertheless, after these encouraging results, more effort has been invested into fabricating highly transparent ceramic Nd : YAG that can compete with single crystal Nd : YAG. Highly efficient end-pumped ceramic Nd : YAG lasers, which are comparable in efficiency with single crystal Nd : YAG lasers, were developed in 2000 and 2001 [6, 7]. Side-pumped ceramic Nd : YAG rod lasers have also been developed in the last three years, over which time output power has gradually increased from 31 W to 72 W to 88 W using our 290 W virtual point source (VPS) pumping system [3, 8, 9]. But in previous work, the laser performances of high power ceramic Nd : YAG lasers were lower than those of high power single crystal Nd : YAG lasers.

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2 Experiments

In this paper, a high-power continuous-wave (cw) ceramic Nd : YAG rod laser is presented. Thanks to the improved optical quality of the ceramic Nd : YAG rod, high power cw laser output of 110 W at 1064 nm wavelength was obtained with a slope efficiency comparable to that of single crystal Nd : YAG rod lasers.

The NTVS method is at the core of the ceramic fabrication process [1–3]. An overview of the fabrication process of highly transparent ceramic Nd : YAG is shown in Fig. 1. The fabrication process of a ceramic Nd : YAG material involves the following steps. First, aqueous solutions of aluminum, yttrium and neodymium chlorides are mixed together. This mixed aqueous solution is added dropwise and then mixed with an aqueous solution of ammonium hydrogencarbonate. Then steps of filtration and washing with water are repeated several times and the resulting material is then dried for two days at ≈ 120 °C. The obtained precursor, consisting of 10-nm-size particles, is calcinated at ≈ 1200 °C to produce the Nd : YAG raw oxide powder, with a particle size of 100 nm. This powder is milled with solvent, binder and dispersion medium for 24 hours. The milled slurry is put in a gypsum mold and dried to obtain the desired form. Finally, after removing the organic components by calcination, the remaining material is vacuum-sintered at 1800 °C, after which highly transparent ceramic Nd : YAG is obtained. The average grain size in this ceramic is about 3–4 μm. The sintering time varies from 5 to 20 hours depending on the size of samples.

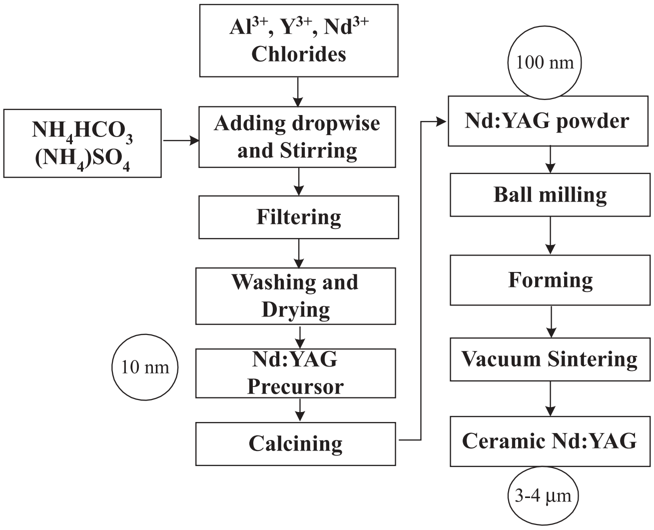

FIGURE 1 Brief overview of the fabrication process of highly transparent Nd : YAG ceramics

The pumping geometry used in this work is the VPS (virtual point source) previously described [10–12]. A schematic diagram of the VPS and the Nd : YAG laser cavity is shown in Fig. 2. In this set-up, 32 sets of 10 W laser diodes emitting at 807 nm were used to form a symmetrical ring-shaped pumping source, enabling angular pumping uniformity. With a maximum pump power of 290 W for this set-up, a maximum output power of 105 W was previously reported using a 0.6 at. % single crystal Nd : YAG rod (φ 4 mm × 104 mm) purchased from Litton-Airtron [13].

The rod and pumping apparatus was placed in a laser cavity consisting of two concave mirrors, each having a 500-mm radius of curvature. One mirror was highly reflecting while the output mirror had 10% transmission at the lasing wavelength. The cavity length was about 540 mm. The sample used in this experiment was a 4-mm diameter, 105-mm long ceramic YAG rod with 0.6% Nd concentration. The end faces of the rod were flat and antireflection-coated at 1064 nm. A 0.6 at. % Nd : YAG single crystal rod (purchased from II-VI Inc.) with the same size and the same coatings was also used in this experiment for a comparison.

Figure 3 shows the laser output power at 1064 nm versus incident pump power. The lasing threshold was found to be 16 W. When the pump power reached 290 W, a cw laser output power of 110 W was obtained. The slope efficiency was found to be around 41%. With the single crystal rod, the maximum output power was 103 W and the slope efficiency was about 38%. The measured beam propagation factors M^2 for ceramic and single crystal rods at maximum output power were found to be about 6. This result indicates that the quality of our ceramic Nd : YAG laser rod is comparable to, if not better than, that of a single crystal Nd : YAG laser rod.

A laser oscillation experiment was also carried out on the same ceramic rod over a longer period of time. Laser oscillation with pump power of 214 W was maintained for 24 hours. The initial output power was 81 W. After 24 hours, the same output power was found. This result suggests that lasing of high-power diode-pumped ceramic material can be sustained over long periods of time.

For high power Nd : YAG rod lasers, the homogeneity of the long laser rod is a very important factor. At high pump power, the inhomogeneity and internal strain in the laser rod can cause some depolarization and phase distortion of the laser beam, resulting in higher cavity losses, low laser efficiency and poor beam quality. In order to check the homogeneity of our ceramic rod, several ceramic rods produced at different times were put between two polarizers, and polarization extinction ratios (PER) were measured without pump power. The PER is defined as the ratio of power transmitted by the device when the polarization axes are aligned compared with the condition when the axes are crossed. $PER\,(\mathrm{dB}) = 10\log_{10}(P_{//}/P_{\perp})$, where $P_{//}$ is transmitted power when the polarization axes are aligned, $P_{\perp}$ is transmitted power when the polarization axes are crossed. The wavelength of probe light was 1064 nm. Figure 4 shows the PER of ceramic Nd : YAG rods, which have been produced since the year 2000. The PER of the single crystal rod used in this work is also shown for comparison. Under a VPS pump power of 290 W, maximum output powers of 18 W, 31 W, 72 W, 88 W and 110 W were obtained from the ceramic rods produced at different times, respectively. From the figure, one

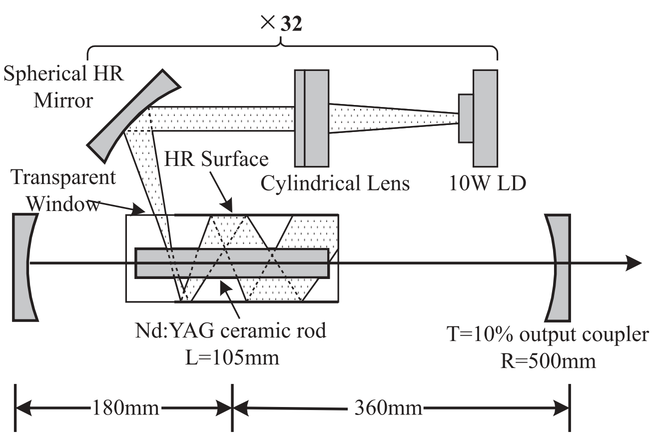

FIGURE 2 Schematic diagram of Nd : YAG laser cavity and the virtual point source (VPS) pumping system

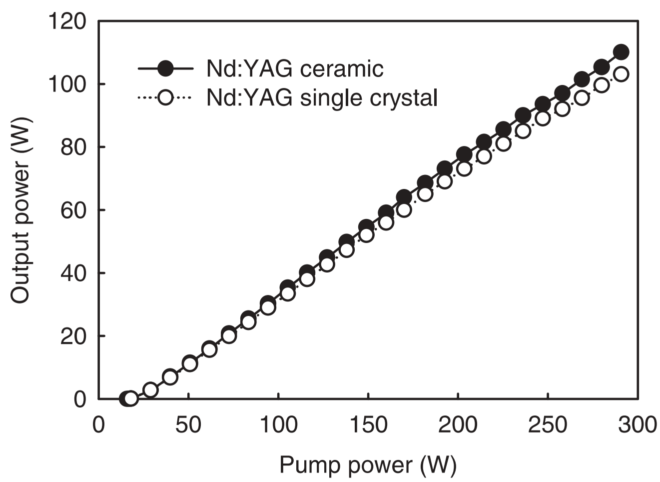

FIGURE 3 Input-output curve of ceramic and single crystal Nd : YAG rod lasers

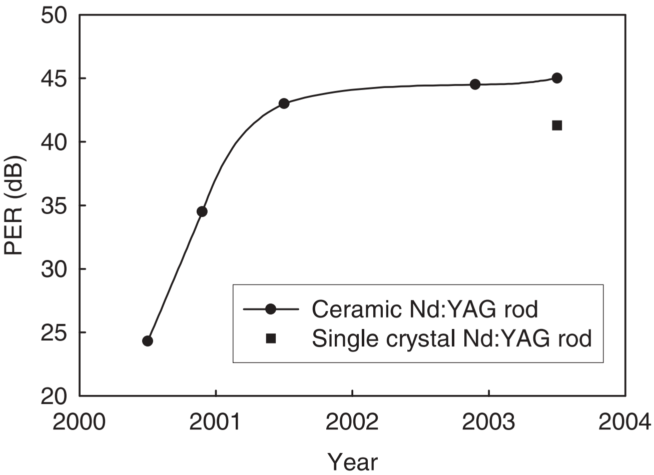

FIGURE 4 Polarization extinction ratios (*PER*) of ceramic Nd : YAG rods produced at different times. Data for the single crystal Nd : YAG rod is shown here for comparison

can see that because of the improvement in the homogeneity of ceramic rods, the output power has increased accordingly.

3 Discussion

How can such modern ceramic technology produce laser material with an optical quality equaling or even exceeding that of material grown from the melt? In principle, the quality of ceramics cannot exceed that of single crystals because the polycrystalline structure contains grain boundaries that are almost absent in single crystals. However, it is worthwhile noting that the grown single crystals also intrinsically contain all kinds of defects such as dislocations, vacancies and inclusions, contamination from the crucible, and so on. Growing single crystals is a time consuming, expensive and size-limited procedure. The number of defects tends to grow at higher crystal growth rate, making it extremely difficult to grow large single crystals with good optical quality. Several methods are used to grow single crystals, such as Czochralski, Bridgman, flux or LHPG [14–16]. Some of them, such as the flux method, yield single crystals with good quality, but at the expense of growth rate, while some other methods, such as the Czochralski and Bridgman methods, make it possible to increase crystal growth rate up to several hundred micrometers per hour, enabling the fabrication of samples of larger size but with mitigated quality. Single crystals of Nd : YAG obtained by the Czochralski or Bridgman melting methods practically always have the facet structure, which occupies a large central or peripheral part of the bulks. Therefore, the useful volume (for cutting laser rods or slabs) of these crystals is much less than the grown volume. Usually the cutting loss is more than 50%, although the facet structure can still be seen in some commercial crystals. Figure 5a shows the wavefront distortion picture of a single crystal Nd : YAG slab near the facet part measured by a Zygo interferometer. From this figure, one can see that near the facet part, the wavefront was seriously distorted. But for a ceramic Nd : YAG slab, because there is no facet problem, the wavefront distortion picture (shown in Fig. 5b) shows a homogeneous pattern, which is much better than that of a single crystal.

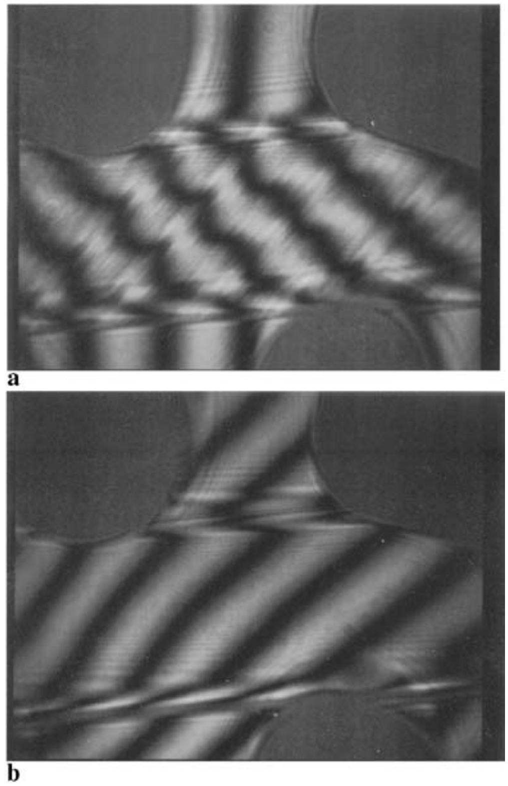

FIGURE 5 **a** Transmitted wavefront distortion for a single Nd : YAG slab; **b** Transmitted wavefront distortion for a ceramic Nd : YAG slab

In the fabrication process of transparent ceramic Nd : YAG, the Nd : YAG fine powder for sintering has a particle size of about 100 nm. The driving force offered by the surface energy differences between curved boundary sides of such small particles is sufficient for the compactness of ceramic Nd : YAG [17]. In this case, no external press is required during the fabrication process. This is one of the key differences between hot-press and cold-press ceramic fabrication methods [4, 18]. The grain growth rate in our ceramic sintering process is only of the order of 1 μm per hour, which is comparable to the natural crystal growth process. As a result, the defect density is minimized. Moreover, grain boundaries produced using this process are stripped of any secondary phase and can be as thin as one or two atomic layers, resulting in negligible light scattering for isotropic materials. The porosity in our ceramic Nd : YAG has been reduced to less than 1 ppm which is also a great help for reducing the light scattering. Ceramic Nd : YAG has no facet structure. Therefore, by improving the homogeneity of our ceramics, the cutting loss can be reduced to nearly 0. Therefore, at present, the NTVS technology appears to be the only available method that can simultaneously provide higher optical quality and large size.

4 Conclusion

A high-power cw ceramic Nd : YAG rod laser has been demonstrated using a high power VPS pumping system. A cw output power of 110 W at 1064 nm was obtained under 290 W pumping with a slope efficiency of 41%. A comparable laser performance to a high power single crystal Nd : YAG laser was obtained. This similar performance was ascribed to the excellent optical quality of the ceramic sample made by the NTVS method.

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