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# High-Power Nd:$Y_3Al_5O_{12}$ Ceramic Laser

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High power CW (continuous wave) polycrystalline Nd:$Y_3Al_5O_{12}$ (Nd:YAG) ceramic rod laser was demonstrated for the first time. The maximum output power of 31 W with a 18.8% slope efficiency was obtained at 1064 nm using 214.5 W/808 nm laser diode pumping.

KEYWORDS: Nd:YAG ceramics, ceramic laser, diode-pumped, solid-state laser, virtual point source (VPS)

## 1. Introduction

The material types known thus far as solid-state laser hosts are crystals and glasses. Recently, however, polycrystalline Nd:$Y_3Al_5O_{12}$ (Nd:YAG) ceramic laser material has received much attention because of its several advantages.[1–6] For example, a sample with high neodymium concentration ($>$1%) and large size (now $\phi$450 mm × 10 mm is available) can be fabricated, and mass production is possible since neither special techniques nor expensive devices (for example, an Ir crucible for crystal growth) are required during the fabrication of ceramics. In 1995, Ikesue, *et al*. fabricated highly transparent Nd:YAG ceramics using powders of $Al_2O_3$, $Y_2O_3$ and $Nd_2O_3$ with particles smaller than 2 $\mu$m as starting materials.[3] The scattering loss (0.009 $cm^{-1}$) for this sample was sufficiently low to obtain laser output for the very first time. A slope efficiency of 28% was reported with a 600 mW laser-diode (LD) end-pumping scheme. For the fabrication of transparent ceramics, the hot press method, the wet chemical method and the urea precipitation method have been used. Recently, Konoshima Chemical co. Ltd., fabricated Nd:YAG ceramics successfully by a new method.[7,8] The ceramics formation process and the sintering process have been optimized for fabricating highly transparent, high-quality Nd:YAG ceramics. The average grain size diameter is about 10 $\mu$m with a grain-boundary width of less than 1 nm. The porosity in this kind of ceramics is at the 1 ppm level. Such narrow grain-boundary width and very low porosity ensure very low scattering loss inside the ceramic samples. The optical properties, such as the absorption spectrum, emission spectrum and fluorescence lifetime, have been studied before and results almost identical to those of Nd:YAG single crystal were reported. With a small-size 1% Nd:YAG ceramics sample ($\phi$3 mm × 5 mm) and a 1 W laser diode end-pumping scheme, a slope efficiency of 53% has been obtained.[6] In this paper, we demonstrate high-power CW laser oscillation for the first time with a Nd:YAG ceramic rod using a high-power virtual point source (VPS) LD pumping system. A 31 W CW laser output at 1064 nm was obtained using 214.5 W/808 nm pump power.

## 2. Experimental Setup

The pumping geometry used in this work is the VPS, which has been described previously.[9,10] In this setup, 32 sets of 10 W laser diodes (807 nm) were used to form a symmetrical ring-shaped pumping source so as to obtain better angular uniformity. The output of the laser diodes was focused onto a point (or line) at the rod axis by 32 sets of optics, each composed of a cylindrical lens and a high-reflectivity spherical mirror. The axial illuminations are completed by a coaxial cylinder with an Ag-coated side surface and Au-coated end surfaces which, together function as a huge double-clad fiber. The point of focus, acting as a VPS, was imaged and reimaged along the rod axis and reflected by the end surfaces, thus after multiple passes, the entire laser rod was illuminated. A schematic of the laser setup is shown in Fig. 1. The sample used in this experiment is a $\phi$3 mm × 100 mm Nd:YAG ceramic rod with 1% neodymium concentration. The end faces of the rod were flat and antireflection-coated at 1064 nm. Two concave mirrors, both with 500 mm radius, were used to form the laser cavity. One was high-relectivity coated at 1064 nm; the other mirror has a reflectivity of 80% at 1064 nm. The cavity length is about 600 mm.

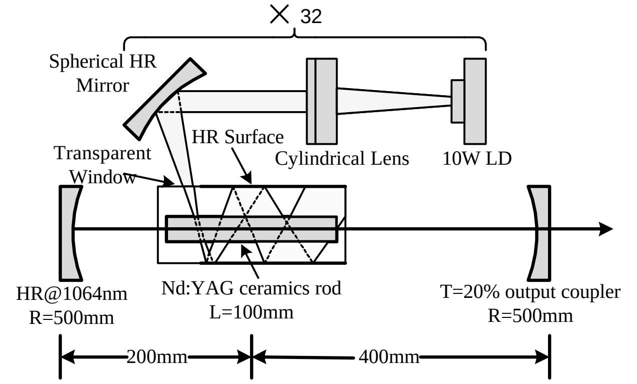

Fig. 1. Schematic diagram of Nd:YAG ceramics laser cavity and the virtual point source (VPS).

## 3. Results and Discussion

The thermal lensing effect can be modeled as an equivalent thin lens at the center of the ceramics rod with an effective focal length of $f_T$. Figure 2(a) shows the resonator stability parameter $g_1g_2$ versus dioptric power (the reciprocal of $f_T$). When the dioptric power approaches 8.3 (corresponding $f_T$ is 120 mm), $g_1g_2$ approaches 1, the edge of the resonator stability region. Figure 2(b) shows the measured dioptric power versus pump power. When increasing

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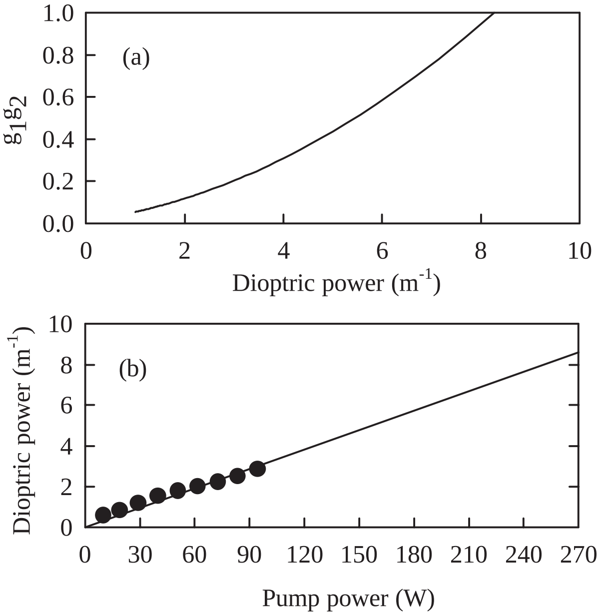

Fig. 2. (a) Calculated resonator stability parameter $g_1g_2$ versus dioptric power; (b) Dioptric power as a function of VPS pump power. Black dots: measured data; solid line: fitted curve.

the pump power to 94 W, the dioptric power increased to 2.9, corresponding to the thermal focal length of 350 mm. The thermal focal length will decrease more with increasing pump power, but because of obstacles in the setup, a thermal focal length less than 350 mm can't be measured in this VPS setup. Since the dioptric power is usually proportional to the pump power, the data in Fig. 2(b) were linearly curve-fitted. From the fitted curve, it is evident that when the pump power increases to about 260 W, the dioptric power approaches 8.3, the edge of the resonator stability region. Figure 3 shows the laser output at 1064 nm versus pump power. The laser threshold is 39.9 W, and when the pump power is increased to 214.5 W, 31 W multi mode CW laser output at 1064 nm was obtained, corresponding to an optical-to-optical efficiency of 14.5%. The slope efficiency is 18.8%. When the pump power was increased above 214.5 W, the output power began to decrease because the very short thermal focal length (estimated to be 120 mm) makes the resonator stability parameter approach the edge of the resonator stability region. The laser output disappeared when the pump power increased up to 247 W, which closely agreed with the calculated results, as shown in Fig. 2. Because the minimum cavity length is 600 mm in this VPS setup, a cavity length of less than 600 mm can't be realized. For such a VPS system, a low-neodymium-concentration Nd:YAG sample is better because at the same pump power, a low-concentration sample has a longer absorption depth, a longer thermal focal length and less thermal distortion loss, thus pump power can be increased and higher efficiency can be expected. A high-power low-concentration (such as 0.6%) Nd:YAG ceramics laser will be investigated in the future.

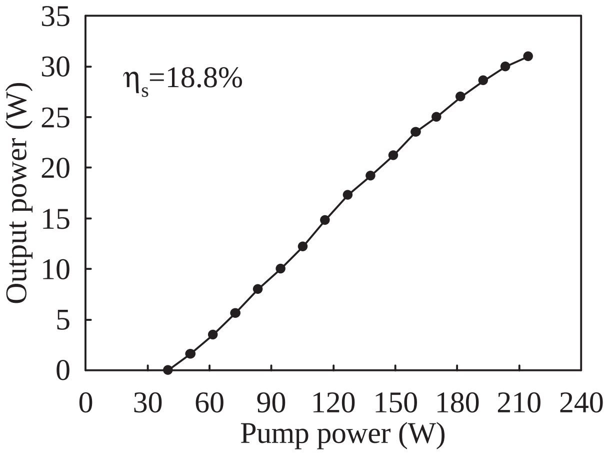

Fig. 3. Nd:YAG ceramics laser output at 1064 nm as a function of VPS pump power.

For high-power Nd:YAG single-crystal lasers, a slope efficiency of more than 30% is usually possible because of the considerable amount of research that has been carried out for decades to improve the quality of Nd:YAG single crystal. For large-size Nd:YAG ceramic rods, the sample homogeneity still needs to be improved. Figure 4 shows the phase-distortion pattern in this ceramic rod without LD pumping. The ceramic rod was placed between cross-polarizers and illuminated by a He–Ne laser. For ideal isotropic materials, there will be no He–Ne light transmitting through the cross polarizers without LD pumping. From Fig. 4, it is evident that some phase-distortion areas exist in the rod. The round white phase-distortion area is caused mainly by the polishing process. The area inside the rod indicated by the arrow pointed is the phase-distortion area that induced the large cavity loss inside ceramics laser rod. The most important concern in ceramics is the scattering loss caused by grain boundaries and pores. According to the Rayleigh equation,[11)] the scattering intensity is proportional to $d^6/\lambda^4$, where $d$ and $l$ are the radius of the scattering body and the measuring wavelength, respectively. In the Nd:YAG ceramics rod used in this experiment, the grain-boundary width (only at the sub nanometer

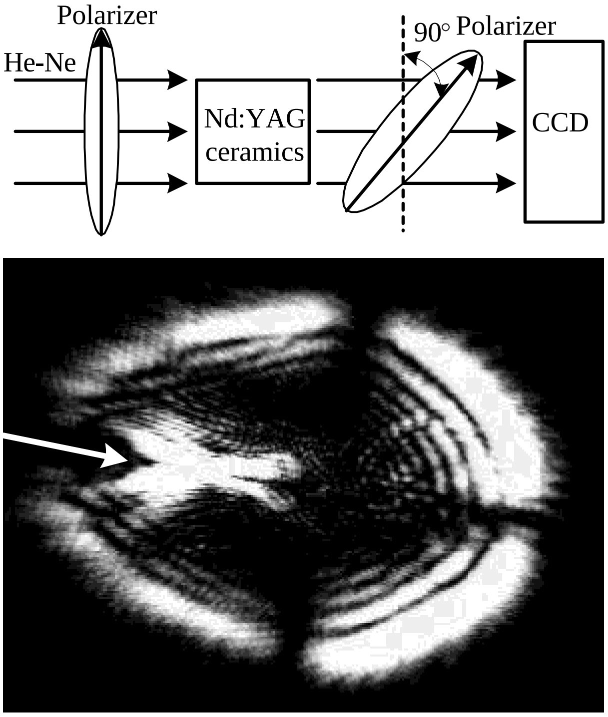

Fig. 4. Phase-distortion area of Nd:YAG ceramic rod. (The cross-polarizers measurement setup.)

level) is much smaller than the lasing wavelength, and the porosity in this ceramics is at the 1 ppm level. Such narrow grain-boundary width and low porosity ensure very low scatting loss and result in high efficiency in small-size end-pumped lasers.[6] For the high-power side-pumping scheme, a long laser rod is usually required. As revealed by the ceramics laser results, the homogeneity of the ceramic rod still needs to be improved in order to decrease the cavity loss so as to obtain much higher laser efficiencies.

## 4. Conclusions

In this paper, we demonstrated a high-power CW Nd:YAG ceramic rod laser using a high-power VPS pumping system for the first time. A 31 W CW laser output was obtained under 214.5 W pumping. The slope efficiency is 18.8%. The quality of the ceramic rod was also analyzed. Currently, the homogeneity of Nd:YAG ceramics still needs to be improved so as to decrease the cavity loss. Now researchers are striving to improve the homogeneity of Nd:YAG ceramics. A high-power Nd:YAG ceramic laser that is comparable in efficiencies with a Nd:YAG single-crystal laser is expected in the near future. Nd:YAG ceramic laser material has several advantages, for example, large-size and high-concentration samples can be fabricated much more easily compared to the single-crystal growth method and also mass production is possible. Therefore Nd:YAG ceramics laser material is a very good alternative to Nd:YAG single crystal.

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