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An exceed 60% efficiency Nd:YAG transparent ceramic laser with low attenuation loss effect

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Here, the attenuation loss effect and laser performance enhancement of Nd:YAG transparent ceramics were investigated. Using a 0.6 at.% Nd:YAG ceramic rod of 3 mm diameter and 65 mm length, the scattering coefficient and absorption coefficient at 1,064 nm were measured to be 0.0001 cm^{-1} and 0.0017 cm^{-1}, respectively. For the 808-nm side-pumped laser experiment, an average output power of 44.9 W was achieved with an optical-to-optical conversion efficiency of 26.4%, which was nearly the same with that of a 1 at% single crystal. Adopting the 885-nm direct end-pumped scheme, the following laser tests demonstrated a high optical efficiency of 62.5% and maximum output power of 144.8 W obtained at an absorbed pump power of 231.5 W. This was until now the highest optical conversion efficiency acquired in an Nd:YAG ceramic laser to our knowledge. It proves that high-power and high-efficiency laser output could be generated by a high-optical quality Nd:YAG ceramic rod along with the 885-nm direct pumping technology.

KEYWORDS

attenuation loss, side-pumped, end-pumped, Nd:YAG ceramic laser, optical conversion efficiency

Introduction

Polycrystalline transparent ceramic materials have become an attractive alternative to widely used single crystals because of their favorable characteristics, such as higher doping concentration, larger scale, more function design freedom, easier manufacture, low cost, and especially superior resistance to fracture [1]. Since an effective laser output with polycrystalline Nd:YAG ceramics was first performed in 1995 [2], numerous attempts have been made in the field of high-power and high-efficiency Nd:YAG ceramic solid-state lasers. These include the output power breaking the 1 kW mark in 2002 and then the remarkable demonstration of more than 100 kW from a YAG ceramic laser system in 2009 [3]. Also, for middle- and high-power laser oscillation, increased optical conversion efficiencies from 14.5% to 52.5% have been reported one by one [4–7]. Among the important milestones, the gain medium with high optical quality is the key factor for highly efficient laser oscillation. Therefore, optical properties including optical

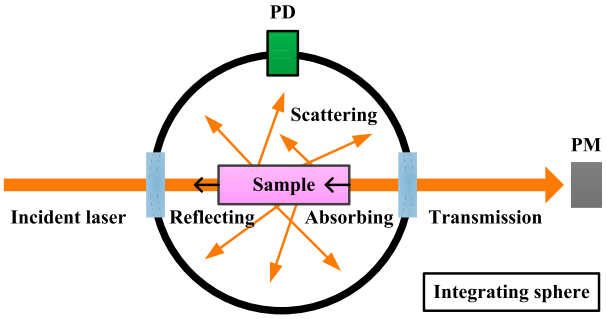

FIGURE 1
Experimental schematic diagram for the scattering coefficient measurements.

absorption, emission spectra, and fluorescence lifetime have been widely studied for Nd:YAG ceramics [8–10], and very similar results were obtained with those of Nd:YAG single crystals. However, the well-known attenuation loss that has enormous influence on the laser performance is rarely available.

Attenuation loss mainly includes the scattering and absorption effect caused by residual pores, grain boundary phases, secondary phases, and impurity ions, which will prohibit the laser output. In 1998, Ikesue et al. showed the scattering coefficients of Nd:YAG ceramics obtained from Fresnel's equation by an optical spectroscopy method [11]. Subsequently, Li et al. presented the absorption coefficients of Nd:YAG ceramics at the laser wavelength [12]. Unfortunately, they did not give a precise distinction between the scattering coefficients and the absorption coefficients. Recently, Boulesteix et al. computed the light scattering of Nd:YAG ceramics according to the Mie light scattering theory. However, the absorption effect was ignored [13]. Providing accurate measurement of the scattering and absorption coefficients could promote the material's research, such as laser experiments and fabrication technology.

This paper introduced an effective measured method of light attenuation loss by means of an integrating sphere technique, which is used to analyze the optical properties of the Nd:YAG ceramic and crystal. A 0.6 at.%-doped Nd:YAG ceramic sample has good optical quality with a scattering coefficient of 0.0001 cm^{-1} and an absorption coefficient of 0.0017 cm^{-1}. Here, an 808-nm laser diode (LD) side-pumped laser configuration was developed, delivering 26.4% of optical efficiency with 44.9 W of output power. Moreover, an end-pumped linear cavity with an 885-nm LD pump was designed to improve the optical conversion efficiency. As a result, a maximum output power of 144.8 W was obtained under the absorbed pump power of 231.5 W. The corresponding optical efficiency was calculated to be as high as 62.5%, which is a significant improvement for high-efficiency Nd:YAG ceramic lasers.

Absorption and scattering coefficient measurement

To assess the overall optical quality of the material, the measurements of light scattering and absorption were carried out at 1,064 nm, based on a homemade scattering loss analyzer with an integrating sphere. The measurement configuration is shown in Figure 1. When a laser beam is nearly at normal incidence upon the samples mounted in the center of the integrating sphere, part of the radiation is reflected, part is scattered, part is absorbed, and the rest is transmitted. The incident laser power was denoted to be P_{in}, and the scattering power and absorption power in the material were described as P_s and P_a, respectively. The transmission power passing through the samples was defined as P_T, and the Fresnel reflection coefficient of the front and back surfaces of the samples was denoted to be r. According to the law of Fresnel reflection and Lambert–Beer [14], the correlated relationship of the aforementioned power distributions can be written as

$$\begin{cases} P_T = (P_{in} - rP_{in} - P_a - P_s)(1-r) \\ P_a + P_s = P_{in}(1-r)\left[1 - \exp(-\alpha L)\right] \end{cases} \tag{1}$$

where α is the attenuation coefficient of the sample and L is the length of the sample. Considering the power loss along the beam propagation in the samples, it is evident that the scattering power P_s and absorption power P_a inside the sample are caused by the scattering and absorption mechanisms, respectively. Thus, we could obtain $\alpha = \alpha_a + \alpha_s$ and $P_a/P_s = \alpha_a/\alpha_s$, where α_a and α_s are the absorption coefficient and the scattering coefficient, respectively. After simplifying Eq. 1, we obtain

$$\begin{cases} \dfrac{P_T}{P_{in}} = (1-r)^2 - \dfrac{P_s}{P_{in}}\left(\dfrac{\alpha_a}{\alpha_s} + 1\right)(1-r) \\ \dfrac{P_s}{P_{in}}\left(\dfrac{\alpha_a}{\alpha_s} + 1\right) = (1-r)\{1 - \exp[-(\alpha_a + \alpha_s)L]\} \end{cases} \tag{2}$$

where P_{in} and P_T were measured by a power meter PM (NOVA II OPHIR). The scattered light intensity with and without the samples was collected using a calibrated photoelectric detector PD (Thorlabs Inc., DET200) mounted at the top of the integrating sphere, recorded as P_1 and P_2, respectively. Also, the output aperture of the integrating sphere was opened for measuring P_1 and closed for measuring P_2. Here, the value of P_s/P_{in} is equal to the ratio of P_1/P_2. By solving Eq. 2, the absorption coefficient α_a and the scattering coefficient α_s could be achieved.

In the measurement, two Nd:YAG ceramic samples with 0.6 at.% and 1.0 at.% doping concentrations and a Nd:YAG single crystal with 1.0 at.% doping concentration were employed, which were fabricated by the Nanyang Technological University. Each sample has a size of 3 mm diameter and 65 mm length, and both facets of samples are polished and antireflection-coated at 1,064 nm to reduce the surface reflection. Therefore, the reflectivity r at the surface of the sample is assumed to be about 0.1%.

TABLE 1 Measured values and correlative results at 1,064 nm of different samples.

Parameters	Samples		
	S1	S2	S3
Material	Ceramic	Ceramic	Crystal
Nd^{3+}-doped concentration (at%)	0.6	1.0	1.0
Ratio of transmittance (P_T/P_{in}, %)	0.986	0.981	0.987
Ratio of scattering (P_s/P_{in}, %)	0.0007	0.009	0.007
Scattering coefficient (α_s, cm^{-1})	0.0001	0.0014	0.0011
Absorption coefficient (α_a, cm^{-1})	0.0017	0.0012	0.0006
Attenuation coefficient (α, cm^{-1})	0.0018	0.0026	0.0017

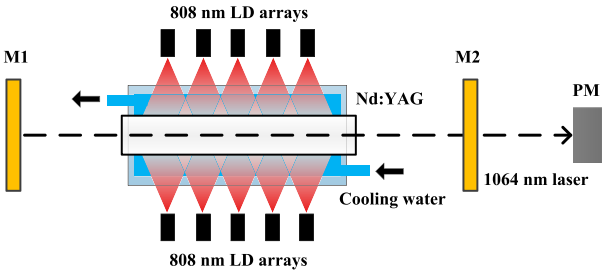

FIGURE 2
Experimental setup of the 808-nm LD side-pumped Nd:YAG laser.

Table 1 shows the corresponding scattering coefficient and absorption coefficient of each sample. Obviously, the crystal sample has the highest optical quality with the smallest attenuation coefficient of 0.0017 cm^{-1}, where the scattering coefficient and absorption coefficient were measured to be 0.0011 cm^{-1} and 0.0006 cm^{-1}, respectively. Compared with the 1 at.% Nd:YAG ceramic rod, the 0.6 at.% Nd:YAG ceramic rod with an attenuation loss of 0.0018 cm^{-1} is nearly the same as the single crystal, which could be easier to produce high-power laser output. In addition, the existence of low impurity ions during the preparation process is inevitable, which results in a large absorption coefficient with a same order of magnitude as the scattering coefficient and could not be neglected in the defects of the ceramic materials. The aforementioned data indicate that ceramic YAG is essentially identical to single-crystal YAG in optical properties measured, especially for the low scattering and absorption losses.

Laser experiment

In order to evaluate the laser performance of the ceramic samples compared with the Nd:YAG crystal, a compact flat–flat cavity was adopted, and the Nd:YAG ceramic was side-pumped with an LD at a wavelength of 808 nm for high pump absorption efficiency. The laser experimental configuration is shown in Figure 2. The samples were surrounded by arrays of diode lasers with a total pump power of 180 W. The Nd:YAG rod and LD arrays were cooled to 25°C with flowing deionized water to match the pump radiation wavelength of the LD and the 808.5 nm absorption spectrum of Nd:YAG. The mirror M1 was coated with high reflectance (HR) at 1,064 nm, and the mirror M2 was an output coupler with partial reflectivity of 80% at 1,064 nm. The 1,064 nm output power was monitored using the PM. The total cavity length is about 70 mm.

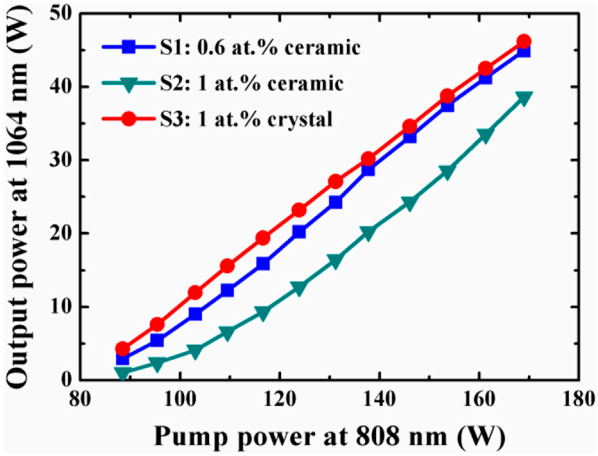

FIGURE 3
Output power of the 1,064-nm laser versus pump power at 808 nm.

The average laser output power of three Nd:YAG samples as a function of LD pump power at 808 nm is shown in Figure 3. The output power increases approximately linearly with the increase in pump power and does not show any roll-over effect, indicating that higher output can be achieved with increasing pump energy continuously. With maximum pump power of 170 W, 44.9 W and 46.2 W laser outputs were obtained at 1,064 nm for the 0.6 at.% Nd:YAG ceramic and 1 at.% Nd:YAG crystal, respectively. The corresponding optical-to-optical conversion efficiencies are 26.4% and 27.2%. The optical efficiency of the 0.6 at.% ceramic laser is only 0.8% less than that of the single-crystal laser, due to the difference in the absorbed pump power caused by different neodymium concentrations. It was proven, from the aspect of output power and laser efficiency, that the ceramic and crystal materials share almost the same laser characteristics. For the 1 at.%-doped ceramic sample, a laser output of 38.6 W was lower than that of the same doping concentration of the crystal because of the largest attenuation loss coefficient and serious thermal effect.

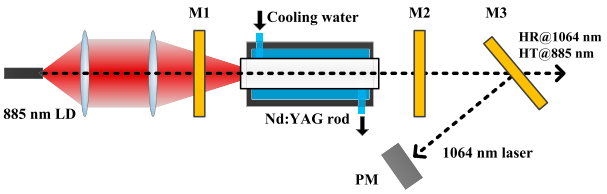

FIGURE 4
Experimental setup of 885-nm LD end-pumped Nd:YAG laser.

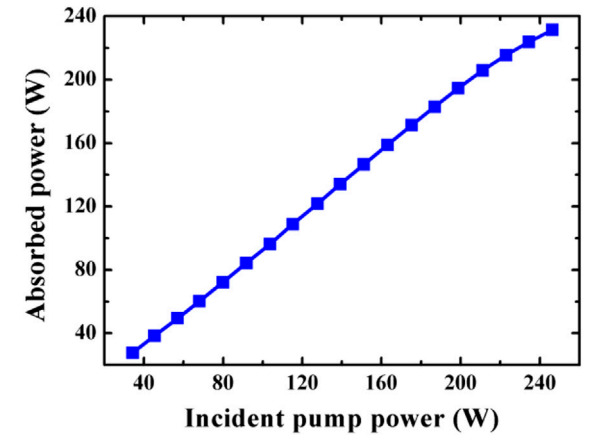

FIGURE 5
Absorbed power versus incident pump power at 885 nm.

The quantum defect between the pump and laser emission wavelength is one of the major factors that limit the LD-pumped solid-state lasers from generating high power and high efficiency [15]. Compared to traditional 808 nm pumping, adopting 885-nm diodes will have a reduction in the thermal load by nearly 30% and will thus lead to an improvement in the overall laser efficiency. The 0.6 at.% Nd:YAG ceramic rod was employed as the measured sample, and an end-pumped plane–plane linear cavity was designed. Figure 4 shows the schematic diagram of the laser oscillation measurement. An 885-nm fiber-coupled diode laser (DILAS, 400 μm diameter and 0.22 NA) was used as the pump source, delivering the maximum power of 250 W. It is focused into the ceramic sample using a coupling lens of 1:1. The laser sample was cooled by the re-circulating filtered water at 16°C, in order to effectively alleviate the thermal effect of the gain medium. The input mirror M1 was coated with a high-transmission film at a pump wavelength of 885 nm and an HR film at 1,064 nm. Also, the output coupler M2 has a transmission of 20% at 1,064 nm. The cavity length of the resonator is about 73 mm to keep the cavity mode in the sample matching the pump mode. The mirror M3 is adopted to separate the pump light and output laser.

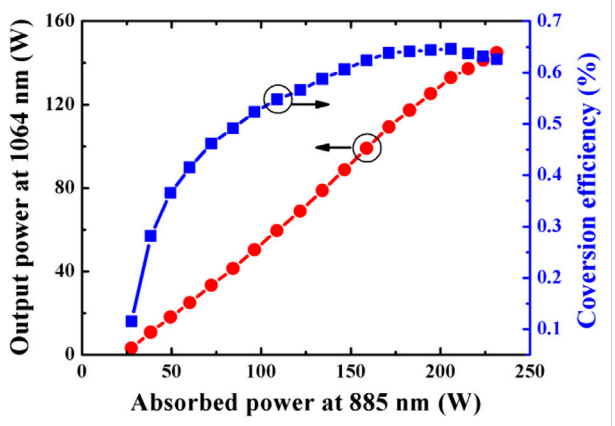

FIGURE 6
Output power of the 1,064-nm laser versus absorbed power at 885 nm.

The optical efficiency for a reasonable comparison could be calculated based on the absorbed pump power. First, the absorbed pump power was estimated by monitoring the pump power passing through the sample at different incident levels, as shown in Figure 5. The absorption power increased and the absorption coefficient decreased with increasing the input pump power. For instance, the absorption coefficient varied from 0.6 cm^{-1} to 0.43 cm^{-1} and corresponds to a pump absorption of 97.9% and 94%, which is attributed to the absorption saturation behavior of a lower doping concentration.

As shown in Figure 6, the output power at 1,064 nm increased linearly in accordance with the absorbed pump power. At the absorbed pump power of 231.5 W, the maximum output power was as high as 144.8 W, with a corresponding optical-to-optical conversion efficiency of 62.5%. The optical conversion efficiency versus absorbed pump power is also given in Figure 6. Actually, the maximum conversion efficiency of about 64.6% was obtained at 205 W of absorbed pumping. To the best of our knowledge, this is the highest optical conversion efficiency of all 1,064-nm laser systems with end-pumped laser modules. The main reason for achieving such high efficiency is the lower quantum defect for 885 nm pumping in combination with the effect of good mode matching and high pump absorption for an end-pumped scheme. The decrease in efficiency after 205 W was caused by the serious thermal effect on the laser ceramic rod for high-power operation.

Discussion and conclusion

In conclusion, the comparison of the laser performance of the Nd:YAG ceramics and crystal as well as attenuation loss are introduced and analyzed, based on an integrating sphere and

808-nm LD side-pumped laser experiment. As a result, the Nd:YAG ceramic could be processed to access almost identical optical properties with the single crystal. Moreover, a 0.6 at.% Nd:YAG ceramic rod was further investigated for producing high optical conversion efficiency, by means of 885-nm LD direct end-pumped technology. Under an absorbed power of 231.5 W, the maximum output power of 144.8 W was obtained with an optical efficiency of 62.5%, which is the highest efficiency the 1,064-nm Nd:YAG ceramic laser ever reported.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material; further inquiries can be directed to the corresponding authors.

Author contributions

YS conceived the project. J-QC conducted the experiment. QB wrote the manuscript and all authors contributed to discussions during its preparation. YB and Q-JP supervised the project.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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