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

**Jin-Quan Chang[1,2,3,*], Yu Shen[1,2,*], Qi Bian[1,2,*], Nan Zong[1,2], Ze Lv[1,2,3], Yong Bo[1,2], and Qin-Jun Peng[1,2]**

[1]Key Lab of Solid State Laser, Technical Institute of Physics and Chemistry, Chinese Academy of Sciences, Beijing 100190, China

[2] Key Lab of Function Crystal and Laser Technology, Technical Institute of Physics and Chemistry, Chinese Academy of Sciences, Beijing, 100190, China

[3] University of Chinese Academy of Sciences, Beijing 100190, China

*** Correspondence:**
Yu Shen
shenyu@mail.ipc.ac.cn

Qi Bian
bianqi@mail.ipc.ac.cn

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

**Abstract**

Here, attenuation loss effect and laser performance enhancement of Nd:YAG transparent ceramics were investigated. Using a 0.6 at.% Nd:YAG ceramic rod with 3 mm diameter and 65 mm length, the scattering coefficient and absorption coefficient at 1064 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 same with that of 1 at.% single crystal. Adopting the 885 nm direct end-pumped scheme, the following laser tests demonstrated the high optical efficiency of 62.5% and maximum output power of 144.8 W were obtained at absorbed pump power of 231.5 W. This was up to now the highest optical conversion efficiency acquired in Nd:YAG ceramic laser to our knowledge. It proves that high power and high efficiency laser output could be generated by high optical quality Nd:YAG ceramic rod along with the 885 nm direct pumping technology.

## 1 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 delivered on the field of high power and high efficiency Nd:YAG ceramic solid-state lasers. For example, 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]. And for middle and high power laser oscillation, the increased optical conversion efficiencies from 14.5% to 52.5% have been reported one by one [4-7]. Among the significantly milestone achievements, the gain medium with high optical quality is the key factor for highly efficient laser oscillation. Therefore, optical properties including optical absorption, emission spectra and fluorescence lifetime have been widely studied for Nd:YAG ceramics [8-10], and very similar results were obtained with that 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 include the scattering and absorption effect caused by the residual pores, grain boundary phases, secondary phases and impurity ions, which will prohibit laser output. In 1998, Ikesue et al. showed the scattering coefficients of Nd:YAG ceramics obtained from Fresnel's equation by an optical spectra method [11]. Subsequently, Li et al. presented the absorption coefficients of Nd:YAG ceramics at the laser wavelength [12]. Unfortunately, they did not gave 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 Mie light scattering theory. However, the absorption effect was ignored [13]. Providing accurate measurement of the scattering and absorption coefficient could promote the materials research, such as laser experiment 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 Nd:YAG ceramic and crystal. A 0.6 at.%-doped Nd:YAG ceramic sample has well optical quality with the scattering coefficient of 0.0001 $cm^{-1}$ and absorption coefficient of 0.0017 $cm^{-1}$. Here, an 808 nm laser diode (LD) side-pumped laser configuration was developed, delivering a 26.4% of optical efficiency with 44.9 W of output power. Moreover, an end-pumped linear cavity with an 885 nm LD pumping 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 is calculated to be as high as 62.5%, which is a significant improvement for high efficiency Nd:YAG ceramic lasers.

## 2 Absorption and scattering coefficient measurement

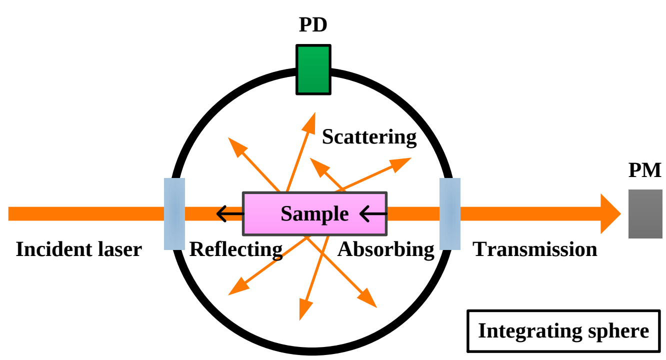


**Figure 1.**Experiment schematic for the scattering coefficient measurements

To assess the overall optical quality of the material, the measurements of light scattering and absorption were carried out at 1064 nm, based on a homemade scattering loss analyzer with an integrating sphere. The measurement configuration was as shown in Figure 1. When a laser beam is nearly at normal incidence upon the samples mounted in the center of 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 respectively described as $P_s$ and $P_a$. The transmission power passing through the samples was defined as $P_T$, and the Fresnel reflection coefficient of the front and back surface of the samples was denoted to be $r$. According to the law of Fresnel reflection and Lambert-Beer [14], the correlated relationship of above 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 $\alpha$ is the attenuation coefficient of the sample, and $L$ is the length of the sample. It is evident that the power attenuation loss inside the sample is caused by the scattering and absorption mechanism. Thus, we could obtain $\alpha=\alpha_a+\alpha_s$, and $P_a/P_s=\alpha_a/\alpha_s$, where $\alpha_a$ and $\alpha_s$ are the absorption coefficient and the scattering coefficient, respectively. After simplifying equation (1), yields

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

While $P_{in}$ and $P_T$ were measured by a power meter PM (NOVA II OPHIR). The scattered light intensity with and without the samples was collected with a calibrated photoelectric detector PD (Thorlabs Inc., DET200) mounted at the top of the integrating sphere, respectively recording as $P_1$ and $P_2$. Here, the value of $P_s/P_{in}$ is equal to the ratio of $P_1/P_2$. By solving equation (2), the absorption coefficient $\alpha_a$ and the scattering coefficient $\alpha_s$ could be achieved.

In the measurement, two Nd:YAG ceramic samples with 0.6 at.% and 1.0 at.% doping concentration, and a Nd:YAG single crystal with 1.0 at.% doping concentration were employed, which were fabricated by 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 1064 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 1064 nm of different samples

| **Parameters** | **Samples** | | |
|---|---|---|---|
| | **S1** | **S2** | **S3** |
| $Nd^{3+}$ 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 ($\alpha_s$, $cm^{-1}$) | 0.0001 | 0.0014 | 0.0011 |
| Absorption coefficient ($\alpha_a$, $cm^{-1}$) | 0.0017 | 0.0012 | 0.0006 |
| Attenuation coefficient ($\alpha$, $cm^{-1}$) | 0.0018 | 0.0026 | 0.0017 |

Table 1 summarizes 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 $cm^{-1}$. Compared with 1 at.% Nd:YAG ceramic rod, the 0.6 at.% Nd:YAG ceramic rod with attenuation loss of 0.0018 $cm^{-1}$ is nearly the same as single crystal, which could be easier to produce high power laser output. In addition, the existence of low impurity ions during 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 above data indicate that ceramic YAG is essentially identical for single crystal YAG in optical properties measured, especially for the low scattering and absorption losses.

## 3 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 side-pumped by LD at the wavelength of 808 nm for high pump absorption efficiency. The samples were surrounded by arrays of diode lasers with the total pump power of 180 W. The Nd:YAG rod and LD arrays were cooled to be 25℃ by deionized water flowing, to match the pump radiation wavelength of LD and the 808.5 nm absorption spectrum of Nd:YAG. The mirror M1 was coated with high reflectance (HR) at 1064 nm, and the mirror M2 was an output coupler with partially-reflectivity of 80% at 1064 nm. The 1064 nm output power was monitored by the PM. The total cavity length is about 70 mm.

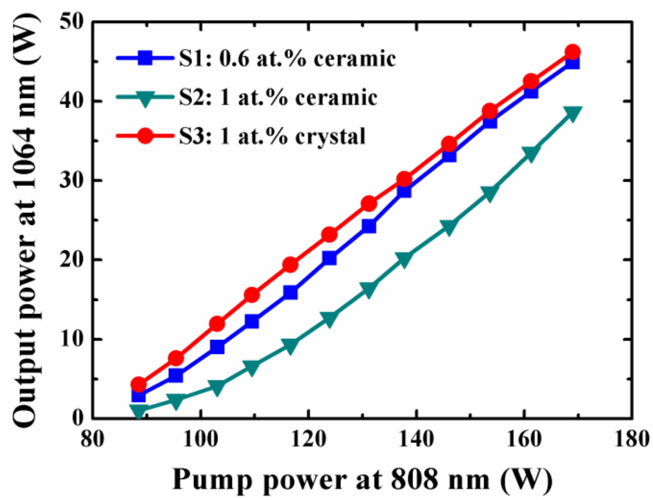


**Figure 2.**Output power of 1064 nm laser versus pump power at 808 nm.

The average laser output power of three Nd:YAG samples as a function of LD pump power at 808 nm is shown in Figure 2. The output power grows approximately linearly with the increase of pump power, and does not show any roll-over effect, indicating that higher output can be achieved with increasing pump energy continuously. With 170 W maximum pump power, 44.9 W and 46.2 W laser output were obtained at 1064 nm for 0.6 at.%Nd:YAG ceramic and1 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 of absorbed pump power caused by different neodymium concentration. It was proven, from the aspect of output power and laser efficiency, the ceramic and crystal materials share almost same laser characteristics.  For 1 at.%-doped ceramic sample, laser output of 38.6 W was lower than the same doping concentration crystal because of the largest attenuation loss coefficient and serious thermal effect.

The quantum defect between the pump and laser emission wavelength is one of the major factors that limit the LD pumped solid-state lasers to generate high power and high efficiency [15]. Compared to traditional 808 nm pumping, adopting 885 nm diodes will have a reduction of thermal load nearly by 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. An 885 nm fiber-coupled diode laser (DILAS, 400 μm diameter and 0.22 NA) was used as the pump source, delivering themaximum power of 250 W. It is focused into the ceramic sample by the coupling lens of 1:1. The laser sample was cooled by the re-circulating filtered water at 16°C. The input mirror M1 was coated with high transmission film at pump wavelength of 885 nm and HR film at 1064nm. And, the output coupler M2 has a transmission of 20% at 1064 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 pump light and output laser.

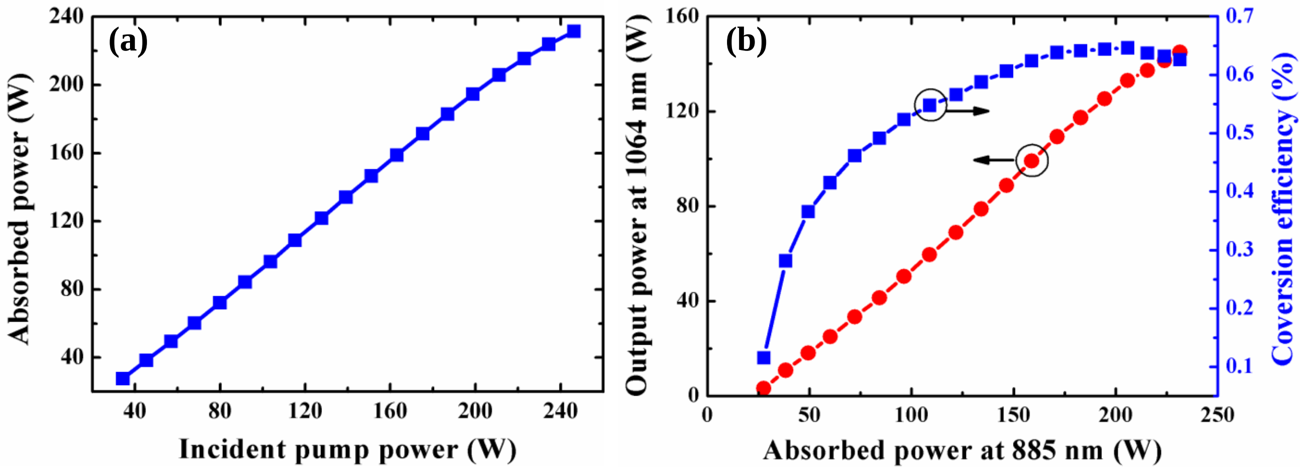


**Figure 3.** (a) Absorbed power versus incident pump power at 885 nm. (b) Output power of 1064 nm laser versus absorbed power at 885 nm.

The optical efficiency for a reasonable comparison could be calculated based on absorbed pump power. Firstly, absorbed pump power was estimated by monitoring the pump power passing through the sample at different incident levels, as displayed in Figure 3(a). 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 $cm^{-1}$, corresponds to a pump absorption of 97.9% and 94%, which is attributed to the absorption saturation behavior of lower doping concentration. As shown in Figure 3(b), the output power at 1064 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 3(b). Actually, the maximum conversion efficiency of about 64.6% was obtained at 205 W absorbed pumping. To the best of our knowledge, this is the highest optical conversion efficiency of all 1064 nm laser systems with end pumped laser modules. The drop in efficiency after 205 W was caused by the serious thermal effect in laser ceramic rod for high power operation.

## 4 Discussion and Conclusion

In conclusion, the comparison of laser performance of 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 the 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 1064 nm Nd:YAG ceramic laser ever reported.

## 5 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.*

## 6 Author Contributions

Yu Shen conceived the project. Jin-Quan Chang conducted the experiment. Qi Bian wrote the manuscript and all authors contributed to discussions during its preparation. Yong Bo and Qin-Jun Peng supervised the project.

## 7 Funding

This work was supported by Supported by the National Key Research and Development Program of China(key special projects, Young Scientist Program, No. 2022YFB3607900 ), Key Laboratory Foundation of Chinese Academy of Sciences, Key Lab of Solid State Laser(No. CXJJ-22S020 ), the National Science Foundation for Young Scientists of China (Grant No. 11504389, 51890864，62005295). The authors acknowledge some crystal support from Chengdu Dien Photoelectric Technology Co., Ltd. (DIEN TECH).

## 8 Acknowledge

The authors acknowledge some crystal support from Chengdu Dien Photoelectric Technology Co., Ltd. (DIEN TECH).

## 9 Reference

1. Lupei V, Lupei A, Ikesue A. Transparent polycrystalline ceramic laser materials. Optical Materials, (2008)30(11), 1781-1786.
2. Ikesue A, Kinoshita T, Kamata K, et al. Fabrication and optical properties of high-performance polycrystalline Nd: YAG ceramics for solid-state lasers. Journal of the American Ceramic Society, (1995) 78(4), 1033-1040.
3. Li J, Pan Y, Zeng Y, et al. The history, development, and future prospects for laser ceramics: A review. International Journal of Refractory Metals and Hard Materials, (2013)39, 44-52.
4. Lu, J. L. J., Song, et al. High-power Nd:Y3Al5O12 ceramic laser. Japanese journal of applied physics, (2000)39(10B), L1048.
5. Qi Y, Zhu X, Lou Q, et al. Nd: YAG ceramic laser obtained high slope-efficiency of 62% in high power applications. Optics Express, (2005)13(22), 8725-8729.
6. Guo W, Cao Y, Huang Q, et al. Fabrication and laser behaviors of Nd: YAG ceramic microchips. Journal of the European Ceramic Society, (2011)31(13), 2241-2246.
7. Lapucci A, Ciofini M, Pucci M, et al. High efficiency, diode pumped 170 W Nd: YAG ceramic slab laser. Journal of the European Optical Society-Rapid Publications, (2011)6.
8. Lu J, Prabhu M, Xu J, Ueda K. I, et al. Highly efficient 2% Nd: yttrium aluminum garnet ceramic laser. Applied Physics Letters, (2000)77(23), 3707-3709.
9. Yagi H, Yanagitani T, Takaichi K, et al. Characterizations and laser performances of highly transparent Nd3+: Y3Al5O12 laser ceramics. Optical Materials, (2007)29(10), 1258-1262.
10. Li J, Wu Y, Pan Y. et al. Solid-state-reaction fabrication and properties of a high-doping Nd: YAG transparent laser ceramic. Frontiers of Chemical Engineering in China, (2008)2(3), 248-252.
11. Ikesue A, Yoshida K. Scattering in polycrystalline Nd: YAG lasers. Journal of the American Ceramic Society, (1998)81(8), 2194-2196.
12. Li J, Wu Y, Pan Y, et al. Fabrication, microstructure and properties of highly transparent Nd: YAG laser

ceramics. Optical Materials, (2008)31(1), 6-17.

13. Boulesteix R., Maitre A., Baumard, J. F, et al. Light scattering by pores in transparent Nd: YAG ceramics for lasers: correlations between microstructure and optical properties. Optics express, (2010)18(14), 14992-15002.
14. Deng W, Yang T, Cao J, et al. High-efficiency 1064 nm nonplanar ring oscillator Nd: YAG laser with diode pumping at 885 nm. Optics Letters, (2018). 43(7), 1562-1565.
15. Koechner, Walter. Solid-state laser engineering. Vol. 1. Springer, 2013.