Investigation on the scattering effect of ceramic Nd:YAG*

Li Cheng-Ming(李成明)[a)†], Zong Nan(宗 楠)[a)b)], Gao Hong-Wei(高宏伟)[a)c)], Xu Zu-Yan(许祖彦)[a)c)], Liu Wen-Bin(刘文斌)[d)], Pan Yu-Bai(潘裕柏)[d)], and Feng Xi-Qi(冯锡淇)[d)]

[a)] *Laboratory of Optical Physics, Institute of Physics, Chinese Academy of Sciences, Beijing* 100190, *China*
[b)] *Graduate School of the Chinese Academy of Sciences, Beijing* 100190, *China*
[c)] *Technical Institute of Physics and Chemistry, Chinese Academy of Sciences, Beijing* 100190, *China*
[d)] *Shanghai Institute of Ceramics, Chinese Academy of Sciences, Shanghai* 200050, *China*

(Received 18 September 2009; revised manuscript received 1 December 2009)

This paper investigates the scattering effect of domestic 0.5 at% ceramic Nd:YAG. An effective method has been utilized to measure the scattering and absorption coefficients. An end-pumped continuous wave (CW) Nd:YAG ceramic laser was also demonstrated. A maximum output power of 6.7 W at 1064 nm was obtained at an 808-nm pump power of 32.9 W. Conversion efficiency and slope efficiency have been achieved. This indicates that scattering has an important effect on the optical performance of ceramic Nd:YAG.

Keywords: Nd:YAG transparent ceramic, light scattering, optical-to-optical efficiency

PACC: 4225F, 4225B, 7820, 8120L

1. Introduction

The transparent polycrystalline neodymium doped Nd:$Y_3Al_5O_{12}$ (Nd:YAG) ceramic is becoming a more and more important substitute for single crystal Nd:YAG because of its inherent virtues.[1] As well as the low cost of production, ceramic Nd:YAG has predominant chemical stability, high temperature stability and it is very easy to be highly doped with the Nd concentration.[2,3] The heat transfer coefficient, the absorption spectra, the emission spectra and the luminescence life of ceramic Nd:YAG are nearly the same as those of single crystal Nd:YAG.[4,5] Furthermore, its exclusive high optical gain, low threshold pump power and excellent optical performance are all very important for its acting as a competing laser material.[6−8] Since the first transparent polycrystalline ceramic Nd:YAG was synthesized in 1995 and gained laser output,[9] it has been developing at a high speed and many scientists are working on research to optimize the growth method; much higher output power has been obtained.[10−12]

Evaluating the optical properties of transparent ceramic materials accurately is crucial. In previous work, most absorption coefficients of the transparent ceramic have been determined without considering the scattering effect.[13,14] However, scattering is never negligible for transparent ceramic. In this article, the scattering effect is investigated quantitatively. We focus on investigation of the scattering effect of ceramic Nd:YAG and single crystal Nd:YAG with an integrating sphere. Scattering and absorption coefficients are obtained, respectively. This gave us more information about the optical performance of ceramic Nd:YAG and it was very helpful for improving the growth technique. The scattering coefficients of ceramic Nd:YAG and single crystal Nd:YAG were 0.08642 cm^{-1} and 0.01236 cm^{-1} at 1064 nm respectively. The maximum output power of end-pump continuous wave (CW) ceramic laser Nd:YAG was 6.7 W. The results indicated that scattering affected the optical performance of Nd:YAG ceramic. The measurement and analytical method of the scattering effect was very effective in evaluating the quality of the laser materials.

2. Experimental method

In our experiments, we measured the scattering coefficient of domestic ceramic Nd:YAG at 1064 nm with an integrating sphere. Another end-pumped CW

*Project supported by the National High Technology Research and Development Program of China (Grant No. 2004CB619006) and the National Natural Science Foundation of China (Grant Nos. 60578030 and 50590404).

†Corresponding author. E-mail: lllcccmmm@semi.ac.cn

© 2010 Chinese Physical Society and IOP Publishing Ltd

Nd:YAG ceramic laser at 1064 nm was also implemented.

The experimental setup of the scattering effect at 1064 nm is shown in Fig. 1. The sample ($3.5\times3.5\times5.72$ cm^3) was put in an integrating sphere. The incident laser entered into the integrating sphere

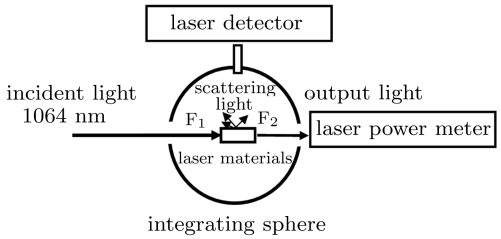


Fig. 1. The experimental setup of the scattering effect of ceramic Nd:YAG.

through an aperture. Then the laser transmitted into the sample and scattered in all different directions. At the position near the output aperture in the same direction as the incident laser, the transmitting optical power was measured with a laser power meter. The internal surface of the integrating sphere was deposited with a thin film of metallic magnesium. The scattering light in all directions was averaged by the smooth film magnesium. As shown in Fig. 1, there was another small aperture in the direction vertical to the incident laser and here the averaged scattering optical signal could be obtained by another laser detector (BPW 34 solar cells). By the signal, the scattering optical power P on the surface of the solar cells could be obtained. After that, all the scattering power could be expressed as

$$P_{\rm sca} = P \cdot S_{\rm in}/S_{\rm C}, \tag{1}$$

where $S_{\rm in}$ is the internal surface areas of the integrating sphere and $S_{\rm C}$ is the area of the laser power meter. The scatterance coefficient S could be obtained as

$$S = P_{\rm sca}/P_{\rm in}, \tag{2}$$

where $P_{\rm in}$ is the incident laser power. In our experiments, the end faces of the Nd:YAG ceramic rod and the Nd:YAG single crystal rod were coated with a thin antireflective film at 1064 nm. So the scattering coefficient $\alpha_{\rm s}$ could be expressed as

$$\alpha_{\rm s} = -1/l \cdot \ln(1-S), \tag{3}$$

where l was the length of the sample. Furthermore, utilizing the transmittance equation $T = \exp[-(\alpha_{\rm a}+\alpha_{\rm s})\,l]$, we can obtain the absorption coefficient

$$\alpha_{\rm a} = -1/l \cdot \ln T - \alpha_{\rm s}. \tag{4}$$

An end-pumped plane–plane laser cavity was used to evaluate the laser performance of the ceramic; a schematic diagram of the experimental setup is shown in Fig. 2. The sample was inserted between the M_1 and M_2 mirrors. The M_1 was antireflective (AR) coated at 808 nm and high reflective (HR) at 1064 nm. As an output coupling, M_2 was partially reflective at 1064 nm. This laser was pumped by an 808-nm diode laser system including a 200-μm diameter 0.22 NA fibre. The fibre's output face was imaged to a 240-μm diameter spot in the centre of the crystal, focusing in the sample. Both end faces of the sample were coated with a thin antireflective film at 808 nm and 1064 nm.

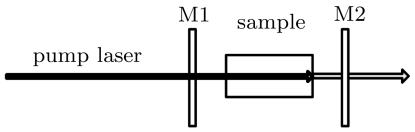


Fig. 2. The experimental setup of ceramic Nd:YAG and single crystal Nd:YAG pumped by an 808-nm fibre module.

3. Experimental results

Firstly, the scattering coefficients of the ceramic Nd:YAG and the crystal Nd:YAG were measured, respectively. The initial power $P_{\rm in}$, the transmittance power $P_{\rm out}$, the scattering power $P_{\rm sca}$ for the ceramic Nd:YAG are listed in Table 1 and the averaged transmittance $T_{\rm r}$ was 86.9%. The curve of the scattering power versus the input power is shown in Fig. 3. The scattering power increased almost linearly with increasing input power. On the rules which have been discussed in the section on the experimental setup, the averaged scattering coefficient for the ceramic Nd:YAG could be worked out to be 0.08642 cm^{-1} at 1064 nm [Fig. 3(a)]. Using Eq. (4), we can calculate out the absorption coefficient and it is $\alpha_{\rm a} = 0.159$ cm^{-1}. However, on the same principle, the scattering coefficient and the absorption of the single crystal Nd:YAG were 0.01236 cm^{-1} [Fig. 3(b)] and 0.08284 cm^{-1}, which are much smaller than those of the ceramic Nd:YAG. This indicates that the scattering effect for the ceramic Nd:YAG was not negligible.

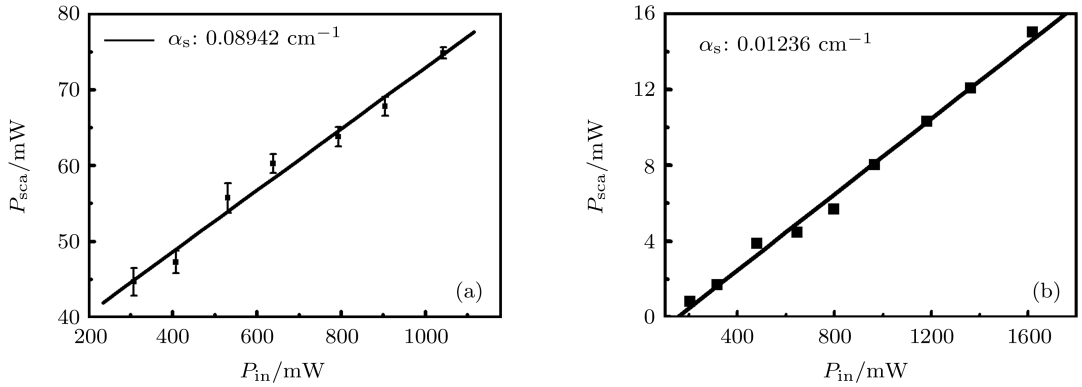


Fig. 3. The scattering effect of ceramic Nd:YAG with a size of 3.5×3.5×5.72 mm^3(a) and single crystal Nd:YAG of the same size (b) at 1064 nm. Here P_{sca} is the scattered power and P_{in} is the incident power.

Table 1. The measured values of the initial power P_{in}, the transmittance power P_{out}, the scattering power P_{sca} for the ceramic Nd:YAG.

P_{in}/mW	407.9	530.8	638.5	793.4	904.5
P_{out}/mW	351.3	450.2	565.9	701.2	783.4
P_{sca}/mW	47.3	55.7	60.2	63.8	67.8
T_r/%	86.12	84.8	88.6	88.4	86.6

Then the laser performance of domestic ceramic Nd:YAG was observed. The output power versus the pump power and the optical-to-optical efficiency were measured and the results are shown in Fig. 4. The maximum output power was 6.7 W when the output coupling was 20%, corresponding to an input power of 32.9 W. The slope efficiency was 20.9% and the optical-to-optical efficiency was 20.4%.

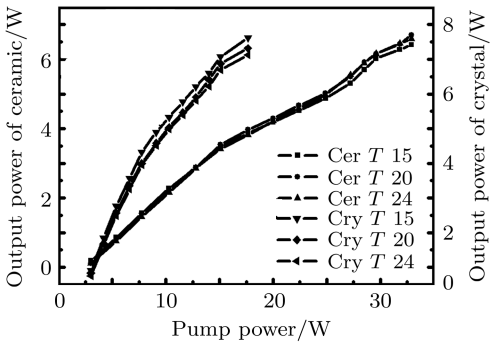


Fig. 4. Output power of ceramic Nd:YAG and single crystal Nd:YAG, the sizes of which were both 3.5×3.5×5.72 mm^3, pumped by an 808-nm fibre laser. Here Cer means the ceramic, Cry means the crystal and T was transmittance of the output coupling.

As a comparison, the maximum output power of single crystal Nd:YAG was 8.01 W, corresponding to an input power of 17.65 W at an output coupling of 15%. The slope efficiency and the optical-to-optical efficiency were 50.82% and 26.7%, respectively. With the output coupling increased from 15% to 24%, the change in the output power was not very evident.

The optical-to-optical efficiency of the single crystal Nd:YAG was almost 30% higher than that of the ceramic Nd:YAG. Furthermore, the slope efficiency for the Nd:YAG single crystal was almost 2.54 times of that for the Nd:YAG ceramic. This indicated that the stronger scattering effect really reduced the optical performance of the ceramic Nd:YAG in comparison with the single crystal Nd:YAG.

4. Summary

In conclusion, the scattering effect of ceramic Nd:YAG and single crystal Nd:YAG at 1064 nm has been investigated by an integrating sphere. An end-pumped CW Nd:YAG ceramic laser, whose emission wavelength was 1064 nm, was completed. It demonstrated that the scattering measurement with an integrating sphere was an effective way to evaluate the property of the materials. The measured sample of the ceramic Nd:YAG was pumped by an 808-nm laser and an output power of 6.7 W was obtained. Single crystal Nd:YAG with the same size and Nd concentration was also measured under the same condition and an output power of 8.01 W was achieved. The scattering effect in the ceramic could not be neglected and it affected the optical performance.

References

[1] Lupei V, Lupei A and Ikesue A 2008 *Opt. Mater.* **30** 1781

[2] Lu J R 2001 *Advanced Solid-State Lasers* **50** 610

[3] Lu J R 2002 *Advanced Solid-State Lasers* **68** 507

[4] Lupei V, Pavel N and Taira T 2002 *Appl. Phys. Lett.* **81** 2677

[5] Zhu H T, Lou Q H, Qi Y F, Dong J X and Wei Y R 2006 *Acta Phys. Sin.* **55** 5221 (in Chinese)

[6] Geusic J E, Marcos H M and Uitert L G V 1964 *Appl. Phys. Lett.* **4** 182

[7] Yokoyama T 1988 *Bull. Ceram. Soc. Jpn.* **23** 461

[8] Zhu H T, Lou Q H, Qi Y F, Ma H X, Dong J X and Wei Y R 2005 *Acta Phys. Sin.* **54** 5648 (in Chinese)

[9] Ikesue A, Kinoshita T and Kamata K 1995 *J. Am. Ceram. Soc.* **784** 1033

[10] Wang D W, Zhang D Q, Yuan J, Zhao Q L, Liu H M, Wang Z Y and Cao M S 2009 *Chin. Phys.* B **18** 2596

[11] Xiao C J, Chi Z H, Li F Y, Feng S M, Jin C Q, Wang X H, Deng X Y and Li L T 2007 *Chin. Phys.* **16** 3125

[12] Lan R J, Liu H, Wang Z P, Ren Q, Zhang H J, Wang J Y, Yu H H, Lü Y H, Sang Y H and Xu X G 2009 *Acta Phys. Sin.* **58** 7686 (in Chinese)

[13] Ikesue A 2002 *Opt. Mater.* **19** 183

[14] Yang Q H, Ding J, Zhang H W and Xu J 2007 *Opt. Commun.* **273** 238