Comparison of laser performance of electro-optic Q-switched Nd:YAG ceramic/single crystal laser

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An electro-optic Q-switched Nd:YAG ceramic laser operating at kHz repetition rate was demonstrated. Thermal induced lens' focus of ceramic rod was measured and compensated by plano-convex cavity structure. Depolarization loss at different output powers was measured in Nd:YAG single crystal and ceramic lasers. High-energy high-beam-quality laser pulse output was obtained in both laser structures. Pulse energy of about 20 mJ and pulse width of less than 12 ns were achieved, and the average power reached 20 W. The divergence of output laser beam was less than 1.2 mrad, and the beam propagation factor M^2 was about 1.4.

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People have tried to use ceramics as laser materials since 1960s, and have done many studies. But until 1995, Ikesue *et al.* fabricated transparent polycrystalline Nd:YAG ceramics using high purity material by solid reaction process[1], whose average grain size was 50 μm and relative density was 99.98%. A laser output of 70 mW was firstly lased by Nd:YAG ceramics. In 1999, high transparent and high optical quality Nd:YAG ceramics were made by nano-technology and vacuum sintering technology (NTVS)[2,3]. The Nd:YAG ceramic has the same absorption line, emission line, and fluorescent lifetime as single crystal, which is less expensive and can be fabricated more easily with high doping concentration in large size.

Based on the innovative progress of the ceramics' research, ceramic laser has developed rapidly in recent years. The highest output power of high-power high-efficiency continuous wave (CW) diode-side-pumped ceramic laser was reached to 1.46 kW[4,5], whereas in 1995 only 70 mW was obtained. It has been proven that most of the physical and optical parameters of Nd:YAG ceramics fabricated by NTVS method were similar to those of Nd:YAG single crystal[6], such as thermal conductivity, fluorescence lifetime (234 μs), absorption spectrum, emission spectrum, and extinction ratio ($> 40 : 1$). Therefore, these kinds of Nd^{3+} ceramic materials can also be used for Q-switched laser and obtain high-peak-power pulse output. A laser diode (LD) pumped passively Q-switched Nd:YAG ceramic laser using Cr^{4+}:YAG ceramic as saturable absorber has been demonstrated[7,8]. The average pulse energy of 4 μJ and average peak power of 286 W were obtained, and the pulse width was 14 ns when repetition rate was 18 kHz. Acousto-optic Q-switched ceramic laser was also reported, which stably operated with pulse width of 16.4 ns, peak power of 2.46 kW, and energy per pulse of 40.5 μJ[9]. Omatsu *et al.* reported an acousto-optic Q-switched laser[10], whose output at a repetition rate of 160 kHz was 10 W, pulse width was less than 24 ns, and M^2 factor was about 1.8. But high-peak-power high-repetition-rate electro-optic Q-switched ceramic laser has not been reported. In this paper, a diode-side-pumped electro-optic Q-switched Nd:YAG ceramic laser operating at 1-kHz repletion rate was demonstrated, and more than 20-W average power with pulse width of less than 12 ns were obtained. In experiments, a compact pumping structure was designed as shown in Fig. 1. In this structure, nine laser diode arrays (LDAs) were uniformly arranged side-around the laser rod, and cooled by water flowing in micro-channel heatsink. The laser rod was cooled by water flowing through a glass tube. The advantages of this pumping structure are: a) the pump light can entirely enter into the ceramic rod without transmission optics, then pumping transmission efficiency is enhanced; b) the distribution of pump light can be more uniform due to the symmetrical ring-shaped pumping structure; c) because nine sets of LDAs were employed, the gain distribution can match better with the oscillating modes in the laser cavity, increase output energy, and improve beam quality of the laser. The center wavelength of emission from LDA is 808 nm, which meets the absorption peak of Nd:YAG ceramic material. The Nd:YAG ceramic rod with dopant concentration of 1 at.-% (BAIKOWSKI Corp.) was $\Phi 5 \times 75$ (mm) in size, and both end faces were coated with high-transmission film.

Figure 2 shows the pump light power distribution in the section of Nd:YAG ceramic rod in theory. It shows that the intensity distribution in Nd:YAG ceramic rod is

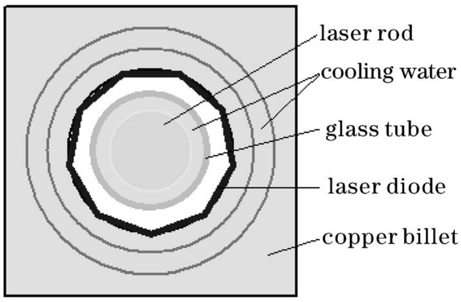

Fig. 1. Around pumping structure.

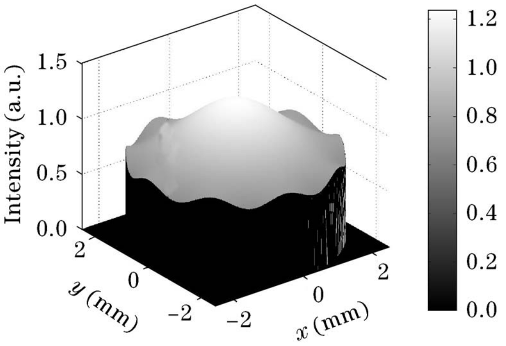

Fig. 2. Light intensity distribution in Nd:YAG ceramic rod.

very uniform around the rod as a result of nine LDAs side-around-pumping structure.

Thermal lens of gain medium induced by high pump power would badly affect the output characteristics of laser, especially the beam quality. So it is necessary to compensate thermal induced lens to improve the performances of laser. In experiment, we measured focus of thermal induced lens of Nd:YAG ceramic rod with different input powers. A wide beam of He-Ne laser propagated through the center axis of ceramic rod was used to determine the focus of thermal induced lens. Figure 3 was the thermal induced lens' focul length as a function of the input power from LDAs. It showed that the thermal lens focus decreased as the input power increasing, and the thermal lens effect became stronger. With input power of 384 W, the focus was measured to be 260 mm. In order to compensate the thermal induced lens effect, we designed a plano-convex cavity. This kind of cavity structure can also increase the oscillation mode volume. According to the measured thermal focus, the thermal stability of cavity can be design with certain radius of M2, as well as the corresponding beam radius (ω_0) and divergence (θ) of fundamental lasing mode[11].

In Fig. 4, M2 was the rear mirror, whose radius was 250 mm. The transmission of plane output mirror (M1) was 70%, and the length of cavity was 240 mm. A polarizer was used to generate linearly polarized light, and those laser radiations not polarized in the proper plane of polarization would be reflected out of resonator. So there would be depolarization loss out from the polarizer due to thermal induced birefringence of laser rod. The depolarization loss power ($P_{\rm dep}$) and the output power ($P_{\rm out}$) were measured simultaneously in Nd:YAG ceramic laser and Nd:YAG single crystal laser, as shown in Fig. 5. From it, we can see that the depolarization loss power at the same output power of single crystal and ceramic was very close. Since the extinction ratio of Nd:YAG ceramic ($> 40 : 1$) was comparable to that of single crystal ($\approx$ 36), both curves showed nearly in linear increasing as the output power rising, and the ratio of $P_{\rm dep}/P_{\rm out}$ was about 0.3 similarly. The experimental results showed that the depolarization loss produced by thermal induced birefringence in ceramic rod was large, and it affected the output power of Q-switched laser seriously.

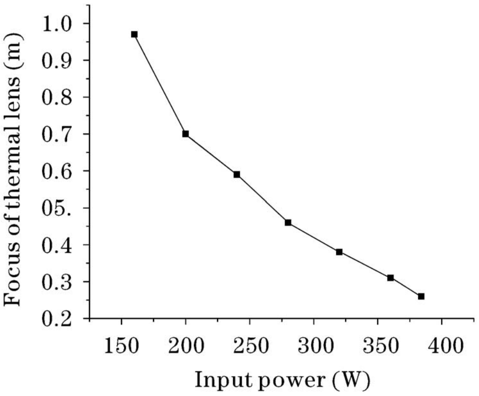

Fig. 3. Thermal induced lens' focus of Nd:YAG ceramic rod with different input powers.

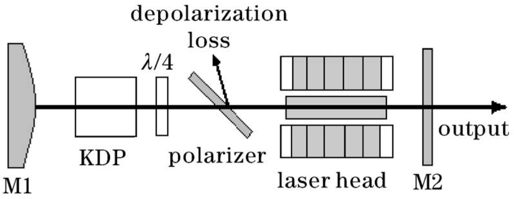

Fig. 4. Configuration of plano-convex cavity.

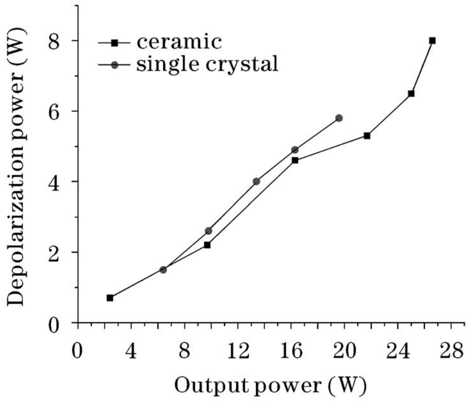

Fig. 5. Depolarization power of single crystal and ceramic rod with different output powers.

Figure 6 showed the curves of output pulse energy of single crystal and ceramic lasers. The output pulse energy of ceramic laser was very close to but a little less than that of single crystal. When the input pulse energy was 390 mJ, the output pulse energy at 1064 nm of single crystal was 22.8 mJ, and that of ceramic laser was 20 mJ.

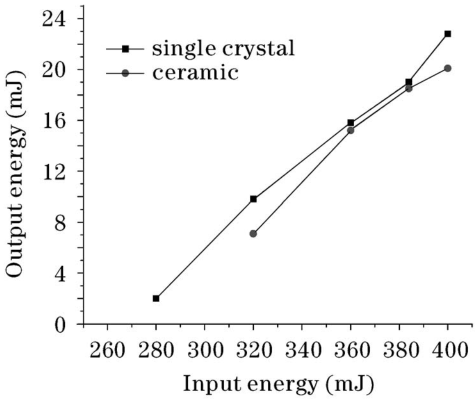

Fig. 6. Output energy of kilohertz Q-switch single crystal and ceramic laser.

The slope efficiencies of single crystal and ceramic laser were 16.7% and 16.5%, almost the same. Their beam divergences were about 1 mrad. It showed that the plano-convex cavity compensated thermal induced lens effectively and Q-switched laser beam with high beam quality was obtained. The output beam diameter of ceramic laser was about 2.7 mm, and the beam propagation factor M^2 was about 1.4.

The pulse profiles of single crystal and ceramic lasers were shown in Fig. 7. The pulse fallen edge of ceramic laser was obviously longer than that of single crystal laser, and the pulse width of ceramic laser was about 12 ns, larger than that of single crystal, which was less than 10 ns. It was mainly induced by light scattering within the micro-pores and grain boundaries in ceramics rod. Finally about 1.67-MW peak power and 20-W average power output from Q-switched Nd:YAG ceramic laser were achieved, respectively.

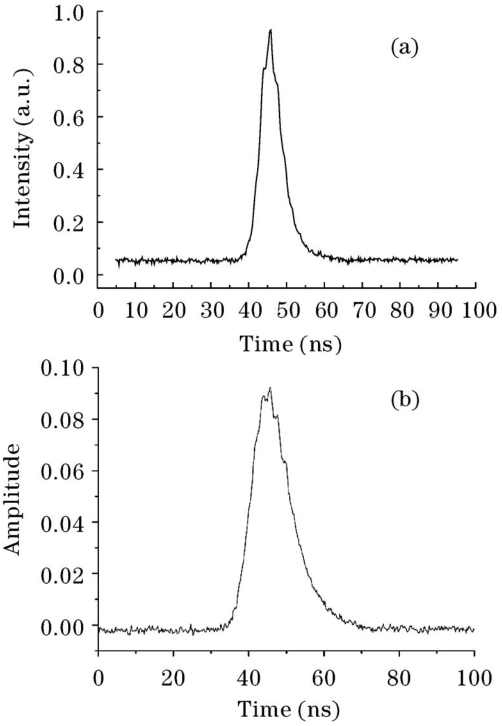

Fig. 7. Waveforms of kilohertz Q-switch single crystal (a) and ceramic (b) laser.

In conclusion, a kHz electro-optic Q-switched Nd:YAG ceramic laser was demonstrated. It produced the energy output pulse of 20 mJ at 1064 nm, and the slope efficiency was 16.5%. The beam divergence was about 1 mrad, and the beam propagation factor M^2 was about 1.4. The pulse width was about 12 ns, and the peak power of output pulse was about 1.67 MW.

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