Investigations and Comparisons of Active Q-Switching Laser Performances of Composite and Conventional Nd:YVO_4 Crystals with Electro-Optic Modulator

Shixia Li, Yufei Li, Shengzhi Zhao, Guiqiu Li*, Xiaomei Wang, Kejian Yang, Tao Li and Dechun Li

School of Information Science and Engineering and Shandong Provincial Key Laboratory of Laser Technology and Application, Shandong University, Jinan 250100, China

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Actively Q-switched laser performances of composite and conventional Nd:YVO_4 crystals were investigated and compared with different Nd-doped concentrations of laser media and different repetition rates of electro-optic modulator. Both continuous-wave and actively Q-switched operations were realized experimentally. At an incident pump power of 7.69 W, the shortest pulse duration of 6.5 ns was obtained by the composite Nd(0.1 at.%):YVO_4/Nd(0.3 at.%):YVO_4/Nd(0.8 at.%):YVO_4 crystal at the repetition rate $f = 2$ kHz. However, the composite Nd(0.1 at.%):YVO_4/Nd(0.5 at.%):YVO_4/Nd(1.0 at.%):YVO_4 laser achieved the maximum average output power of 687 mW at $f = 10$ kHz and the largest single pulse energy of 144 μJ at $f = 2$ kHz. Power saturation of the conventional Nd:YVO_4 crystal was shown during experiment, while no power saturation was observed on the composite Nd:YVO_4crystals, showing good thermo-mechanical performances.

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1. Introduction

Diode-pumped solid-state lasers (DPSSLs) are attractive light sources for many applications because of the high brightness, high efficiency, high reliability, and compact size. Both theoretical and experimental results have demonstrated that the thermal effect of laser crystal such as thermal lens effect, thermal-dependent stress-induced birefringence, and thermal destruction produced by the pumping light is one of the main factors affecting the characteristics of DPSSLs, especially for the end-pumped configuration [1]. In recent years, composite crystal is introduced to reduce the thermal effect. Unlike conventional crystal, composite crystal combines undoped and doped components, which is proved to be a very effective and available means to alleviate the thermal effect owing to the undoped end acting as an effective heat diffuser [2, 3].

Neodymium (Nd)-doped vanadate crystals, just like Nd:YVO_4 [4–12] and Nd:$LuVO_4$ [13, 14] have been proved to be excellent laser materials. In this paper, two composite multi-segmented Nd:YVO_4/Nd:YVO_4/Nd:YVO_4 crystals with increasingly Nd-doped concentrations the first segment Nd(0.1 at.%):YVO_4 being just like an undoped component were employed to reduce the thermal effect. The two composite samples were fabricated by diffusion bonding [15]. This technique has the advantages of no adhesives, less distortion on the bonding interface and flexible manufacture.

In this paper, we report continuous-wave (CW) and active Q-switching (QS) laser performance of two composite and one conventional Nd:YVO_4 crystals. By inserting electro-optic (EO) into the cavity, actively Q-switched laser operation was realized to investigate the influences of Nd-doped concentration of laser crystal and repetition rate of EO modulator (EOM) on the laser performance. As is shown in our report, if employing the proper choice of Nd-doped concentration of the segments in the composite crystal, the active Q-switching laser with shorter pulse duration and larger pulse energy could be obtained due to efficient reduction of the thermal effect and the optimal laser performance of the gain medium. This is the main advantage of applying a combination of increasingly doped Nd:YVO_4 crystals.

2. Experimental setup

The experimental setup is shown in Fig. 1. A commercial fiber-coupled laser diode (FAP system, Coherent Inc., USA) was used as the pumping source, which worked at the maximum absorption wavelength (808 nm) of the Nd ions and the temperature of 20 °C. The output pump light was focused into the gain medium with a spot size of 400 μm in diameter. A plano-concave laser cavity, which was constructed by mirrors M_1 and M_2, was employed in this experiment. The cavity length was experimentally 120 mm. Two composite and conventional Nd:YVO_4 crystals were employed as gain media, as specified in Table. The pump facet of each gain medium was antireflection(AR)-coated at 808 and 1064 nm, while the other facet was AR-coated at 1064 nm.

*corresponding author; e-mail: gqiuli@sdu.edu.cn

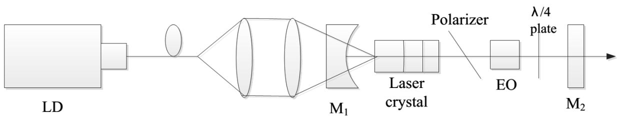

Fig. 1. Schematic diagram of experimental setup.

M_1 (R = 200 mm) was AR-coated at 808 nm on the entrance surface, the other facet was high-transmission(HT)-coated at 808 nm and high-reflection (HR)-coated at 1064 nm. A flat mirror M_2 with transmission of 15% was served as the output coupler (OC). In order to efficiently dissipate the heat deposition, the laser crystals were wrapped with thin indium foil and fitted into water cooled copper holder, maintaining at a constant low temperature of 15 °C during the experiment. An EO modulator (BBO crystal) with a polarizer and $\lambda/4$ plate was employed as active loss modulation and its modulation frequency was adjustable (1–10 kHz). A laser power meter (MAX 500AD, Coherent, USA) was used to measure CW output powers and average output powers. The pulse temporal behavior was recorded by a digital oscilloscope (1 GHz bandwidth and 20 G samples/s sampling rate, Tektronix Inc., USA) and a fast pin photodiode detector with a rise time of 0.4 ns.

TABLE

Specification of crystal blocks used in our laser experiment.

No.	Crystal blocks	Nd^{3+}-doping concentration [at.%]	Dimensions ($b \times c \times a$) [mm^3]
1	$Nd:YVO_4$	1.0	$3 \times 3 \times 10$
2	$Nd:YVO_4$ $+Nd:YVO_4$ $+Nd:YVO_4$	$0.1 + 0.3 + 0.8$	$3 \times 3 \times (4 + 3 + 3)$
3	$Nd:YVO_4$ $+Nd:YVO_4$ $+Nd:YVO_4$	$0.1 + 0.5 + 1.0$	$3 \times 3 \times (4 + 3 + 3)$

3. Experimental results and discussions

We have investigated the passive losses of the three crystals [16] in order to accurately analyze the experimental results. Employing OCs with transmission T = 4%, 6.5%, 15%, 20%, the input-output power dependences in CW regime of operation for the three crystals were achieved and then the slope efficiencies were calculated. Thus passive losses for crystals No. 1, 2, and 3 were calculated to be 3.31%, 2.32%, and 2.14%, respectively.

Figure 2 shows the CW laser output powers of the three crystals. The threshold pump powers were about 0.23, 0.245, and 0.218 W, respectively. Under an incident pump power of 7.69 W, the maximum output powers of the three crystals were 3.08, 3.72, and 3.82 W, correspondingly the slope efficiencies were 43.3%, 51%, and 52.2%, respectively. The output powers of two composite crystals increased linearly with the increase of incident pump power. No power saturation was observed on the two composite crystals. The average effective absorption coefficients for the three crystals were 0.347, 0.377, and 0.478, respectively. Thus the maximal output power was obtained by the No. 3 crystal.

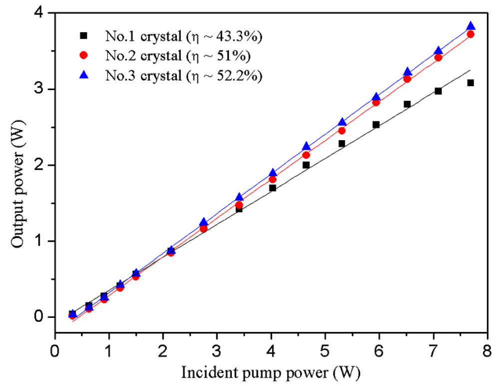

Fig. 2. Output power versus incident pump power.

The beam quality parameter M^2 of the three crystals were measured by the 90.0/10.0 scanning-knife-edge method with $T = 15\%$. For the CW regime, the M^2 for the three crystals were 1.14, 1.13, and 1.11; while the M^2 for QS laser were 1.33, 1.3, and 1.27, respectively. The lasers operating in CW and QS operations were all fundamental modes for the three crystals.

The average output powers are shown in Fig. 3. Compared with composite crystals, the lowest average output power was obtained by the conventional crystal. The average output powers all increased linearly with the increase of the incident pump power. The highest average output power was obtained by No. 3 crystal. The maximal average output powers of 0.621, 0.661, and 0.687 W were obtained by No. 1, 2, and 3 crystals at $f = 10$ kHz, respectively.

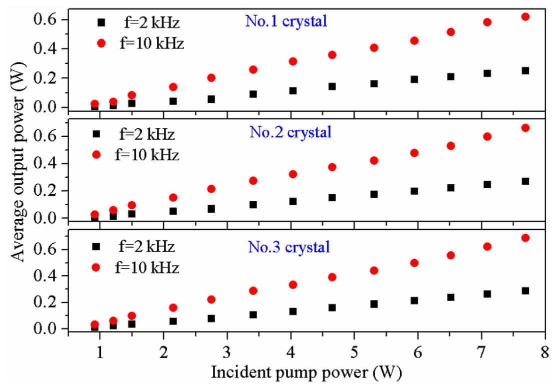

Fig. 3. Average output power versus incident pump power.

Pulse durations versus incident pump power are shown in Fig. 4. Pulse durations of the three crystals at different repetition rate changes not obviously at the same incident pump power. The shortest pulse durations of 7.5, 6.5, and 7.2 ns were obtained by the No. 1, 2, and 3 crystals at $f = 2$ kHz with 7.69 W pump power. Consequently, one can see that the pulse duration of the three crystals at $f = 2$ kHz was shorter than that at $f = 10$ kHz under the identical incident pump power.

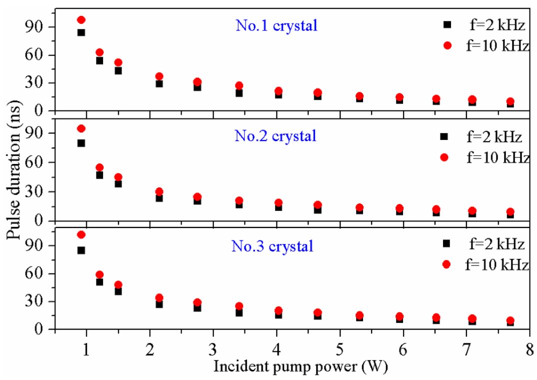

Fig. 4. Pulse duration versus incident pump power.

In the experiment, the temporal pulse profiles for EO Q-switched laser were measured under the incident pump power of 7.69 W at a repetition rate of 2 kHz. Pulses with durations of 7.5, 6.5, and 7.2 ns were obtained by the No. 1, 2, and 3 crystals, which are shown in Fig. 5a–c, respectively.

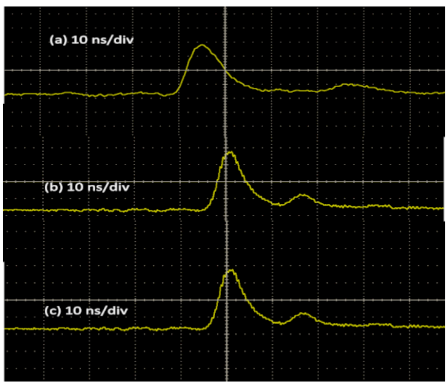

Fig. 5. Pulse traces of the three crystals at $f = 2$ kHz.

The single pulse energy E could be calculated by the average output power P_A and the pulse repetition rate f. Using equation $E = P_A/f$ [17], the single pulse energy E can be calculated, as shown in Fig. 6. As EO modulator, the repetition rate f was settled, therefore, the single pulse energy increased linearly with the increase of the incident pump power, which has the same tendency as the average output power. The maximal single pulse energies of the three crystals were 125, 135, and 144 μJ with $f =$ 2 kHz, respectively. Correspondingly, the highest single pulse energies of 62.1, 66.1, and 68.7 μJ were achieved at the repetition rate of 10 kHz, respectively.

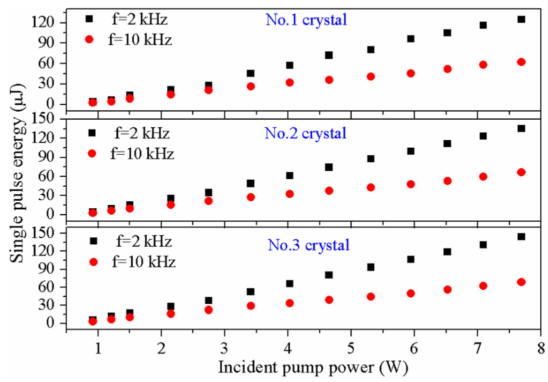

Fig. 6. Single pulse energy versus incident pump power.

Using No. 3 crystal as gain medium, acousto-optic modulator (AOM) was applied to replace the EO modulator to compare the laser performance. Figure 7 depicts the active Q-switching laser characteristics at $f = 2$ kHz for the two modulators. One can see that the average output power and single pulse energy of AOM were higher than those of EOM. But the minimal pulse duration of 7.2 ns was obtained by EOM at an incident pump power of 7.69 W, correspondingly 22.4 ns pulse duration was achieved by AOM. Modulation depth of electro-optic modulator was deeper than that of AOM. Though the single pulse energy of EOM was much smaller than that of AOM (144 to 668 μJ), peak power of 20 kW was obtained by the EOM at an incident pump power of 7.69 W, correspondingly 29.8 kW peak power for AOM.

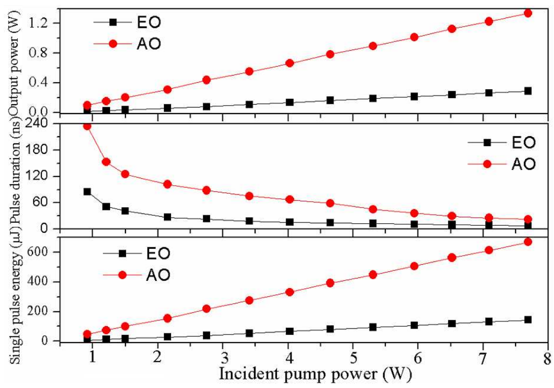

Fig. 7. Average output power, pulse duration, and single pulse energy versus incident pump power.

4. Conclusions

CW and active Q-switching laser performances of two composite and one conventional $Nd:YVO_4$ crystals were investigated for the first time. No power saturations were observed on two composite $Nd:YVO_4$crystals, showing good thermo-mechanical performances. While power saturation of the conventional $Nd:YVO_4$ crystal was shown when the incident pump power exceeded 7.09 W. At an incident pump power of 7.69 W, the maximum CW output power of 3.82 W was obtained by the No. 3 crystal. At the repetition rate of 2 kHz, the highest single pulse energy of 144 μJ was also achieved by the No. 3 crystal under an incident pump power of 7.69 W. Compared with AOM, modulation depth of EOM was much deeper.

Acknowledgments

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