Diode-Pumped High-Repetition-Rate Acousto–Optically Q-switched Nd:YVO₄ Laser Operating at 914 nm¹

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Abstract—A diode-pumped high-repetition-rate acousto–optically (A–O) Q-switched Nd:YVO₄ laser operating at 914 nm was reported in this paper. Employing a compact linear laser cavity, at an operating repetition rate of 10 kHz, a maximum average output power of 2.2 W 914 nm laser was obtained at an incident pump power of 45.3 W, corresponding to an optical conversion efficiency of 4.9% and a slope efficiency of 8.8%. Minimum pulse width of 24 ns and maximum peak power of 8.0 kW of 914 nm laser was also achieved at an incident pump power of 40.8 W. To the best of our knowledge, this is the highest peak power of 914 nm laser at 10 kHz by far. Moreover, the highest operating repetition rate of pulsed 914 nm can even reach 100 kHz.

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1. INTRODUCTION

For the attractive prospect of solid-state lasers around 900 nm and blue lasers by using frequency doubling technology, much attention was paid on improving the performance of continuous-wave (cw) quasi-three-level Nd3+-doped lasers since the first report on diode-pumped 946 nm Nd: YAG laser by Fan and Byer in 1987 [1-12]. Considering the application in remote sensing, pulsed 900 nm lasers will be extremely useful, especially high-repetition-rate operation with a high-peak-power is in demand for improving the speed and distance in transmission. Usually, the technologies of mode-locking or Qswitch were used to generate high-repetition-rate lasers [13-16]. In the past few years, pulsed quasithree-level Nd³⁺-doped lasers had been demonstrated by using passively Q-switch or acousto-optically (A-O) Q-switch. In 2005, Zhang presented the pulsed 946 nm Nd: YAG laser using a co-doped Nd, Cr: YAG as saturable absorber, and the maximum average output power of 2.1 W was achieved with a pulse width of 40.8 ns at a repetition rate of 80 kHz [17]. In addition, passive Q-switched 935 nm Nd:CNGG laser, 938 nm Nd:GAGG laser and 912 nm Nd:GdVO₄ laser were also investigated [18-20]. By means of the A-O Qswitch, our group had demonstrated a pulsed 912 nm Nd:GdVO₄ laser in 2008, with a minimum pulse width of 20 ns and a maximum peak power of 7.1 W at 10 kHz, and pulsed blue laser was also obtained by intracavity frequency doubling [21, 22]. In 2009, Zhang

In this paper, we reported a high-repetition-rate 914 nm Nd:YVO₄ laser using a compact linear laser cavity and a miniature A–O Q-switch. At 10 kHz, a maximum average output power of 2.2 W 914 nm laser was obtained, and a minimum pulse width of 24 ns and the highest peak power of 8.0 kW were also achieved. To the best of our knowledge, this is the highest peak power of 914 nm laser at 10 kHz by far. The repetition rate of pulsed 914 nm can be extended to 100 kHz, then the pulse width was increased to 62.5 ns and the peak power was reduced to 0.92 kW.

2. EXPERIMENTAL SETUP

The experimental setup of diode-end-pumped A– O Q-switched 914 nm Nd:YVO₄ laser is shown in Fig. 1. In our experiments, the pump source was a high brightness fiber-coupled laser diode (HLU110F400, LIMO), which delivered a maximum output power of 110 W at 808 nm from the end of a fiber with 400 μ m

obtained an A–O Q-switched ceramic Nd:YAG laser at 946 nm, with an average output power of 2.64 W at 50 kHz [23]. For 914 nm Nd:YVO₄ laser, Schlatter and Blandin had realized a pulsed operation by using a passively mode-locked technology, giving the repetition rate of 233.8 and 94.0 MHz, the pulse width of 3.0 and 8.8 ps, but the average output power was only 150 and 42 mW, respectively [24, 25]. A–O Qswitched 914 nm Nd:YVO₄ laser had been demonstrated using a V-type cavity, however, the pulse width is too wide at high-repetition-rate operation, resulting in a relative lower peak power [26].

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Fig. 1. Experimental setup of diode-end-pumped A-O Q-switched 914 nm Nd:YVO₄ laser.

core in diameter and a N.A. of 0.22. The pump beam was coupled into the gain medium by a coupling optics, which consisted of two identical plano-convex lenses with a coupling efficiency of 98%. A conventional Nd:YVO₄ crystal with a doping concentration of 0.1 at % and the dimensions of $3 \times 3 \times 6 \text{ mm}^3$ was employed as a gain medium, for low doping concentration and short length crystals can minimize the reloss, up-conversion, absorption concentration quenching and the amplified spontaneous emission (ASE) effect. The crystal wrapped with a 0.05 mm thick indium foil was mounted in a copper microchannel heat sink, and was cooled by water at a temperature of $8.0 \pm 0.1^{\circ}$ C. To prevent the more efficient four-level transitions at 1064 and 1342 nm, both sides of the crystal were coated for high transmission (HT) at 914 nm (T > 99.8%) and 808 nm (T > 99%), while antireflection (AR) coatings at 1064 nm (R < 1%) and 1342 nm (R < 2%) were considered as well. The experiments were carried out with the simple linear cavity. The input mirror M1 had AR coating at 808 nm (R <10%) and high reflection (HR) coating at 914 nm (R >99.8%), the output mirror M2 was highly transmitted at 1064 and 1342 nm, and partially at 914 nm. A 20mm-long A–O Q-switch (Gooch and Housego) was

Average output power at 914 nm, W



Fig. 2. Average output power of A–O Q-switched 914 nm Nd:YVO₄ laser versus incident pump power at the operating repetition rate of 10 kHz.

inserted into the laser cavity to obtain short laser pulse. The Q-switched pulses were recorded by a digital oscilloscope (DPO 7104, Tektronix Inc.) and a fast photodiode (DET 210, Thorlabs Inc.) with a rising time of less than 1 ns. Laser spectra was measured by a fiber spectrometer (HR4000, Ocean Optics Inc.), and output power was recorded by a laser power meter PM30 (PM30, Coherent Inc.).

3. EXPERIMENTAL RESULTS AND DISCUSSION

For improving the output power of A–O Qswitched 914 nm laser, tests were conducted to estimate the best cavity type and output coupling mirror (M2). In the linear cavity, when the concave M1 or M2 (radius of curvature R = 200, 100, and 50 mm) were used, the coating film on the surfaces of A–O Qswitch or Nd:YVO₄ crystal would be damaged, this was because a relative smaller beam waist of oscillating laser was generated in the cavity. Therefore, planar M1 and M2 were used in our experiments, and the output characteristics of pulsed 914 nm laser were measured as the M2 had a transmissivity of T = 6, 9, and 12% at 914 nm. As shown in Fig. 2, it can be seen that the M2 with T = 9% was favorable of achieving high power pulsed 914 nm laser output, and it was higher than that of a cw operation because of instantaneous peak gain was much higher during pulsed operation [27, 28]. Using the cavity with a length of L = 45 mm, the lasing threshold was 23.4 W and the maximum output power of 2.2 W was obtained at an incident pump power of 45.3 W, corresponding to an optical conversion efficiency of 4.9% and an average slope efficiency of 8.8%, respectively. If the low absorption efficiency of the pump radiation ($\eta_{\alpha} = 60\%$) was taken into account, the slope efficiency could be up to 14.7% with respect to the absorbed pump power. When the incident pump power was higher than 45.3 W, the output power of 914 nm laser reduced because of serious thermal lensing effect during the Nd³⁺-doped quasithree-level laser operation, and it would restrict the increase of the cavity length as well.

At 10 kHz, the pulse width and peak power of 914 nm laser as a function of the incident pump power were presented in Fig. 3. We can see that, when the incident pump power was lower than 40.8 W, the pulse

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Fig. 3. Pulse width of A–O Q-switched 914 nm Nd: YVO_4 laser versus incident pump power at 10 kHz.



Fig. 4. Peak power and pulse width of A–O Q-switched 914 nm Nd: YVO_4 laser versus the repetition rate.



Fig. 5. Pulse trains and typical shapes of the 914 nm laser at 10 (a) and 100 kHz (b).

width reduced and the peak power increased exponentially with the increase of the incident pump power. At an incident pump power of 40.8 W, a minimum pulse width of 24 ns 914 nm laser was obtained, with a highest peak power of 8 kW. To the best of our knowledge, this is the highest peak power of 914 nm laser at 10 kHz by far. With the increase of the pump power, the pulse width increased and the peak power reduced, this was attributed to the deterioration of the laser beam quality resulting from thermal effect. At an incident pump power of 49.5 W, the pulse width was 33.6 ns and the peak power was 6.25 kW.

At the incident pump power of 49.5 W, the 914 nm laser performance at different repetition rates (10–100 kHz) was investigated and depicted in Fig. 4. As the increase of the repetition rate, the pulse width was increased and the peak power was decreased. At 100 kHz, the pulse width was increased to 62.5 ns and the peak power was reduced to 0.92 kW. Pulse trains and typical pulse shapes of 914 nm laser at 10 and 100 kHz were shown in Fig. 5. We can see that the pulse amplitudes jittered at 100 kHz operation, which

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indicated the laser gain was not enough to satisfy a stable high-repetition-rate operation, but no lose of pulse was observed if the operating duty cycle for Q-switch was chose properly.



Fig. 6. Laser intensity profile at the maximum average output power of A–O Q-switched 914 nm Nd: YVO_4 laser at 10 kHz.

The 2D and 3D far field laser beam intensity profile of 914 nm laser at the maximum average output power of 2.2 W recorded by a laser beam analyzer (LBA-712PC-D, Spiricon Inc.) was shown in Fig. 6. It can be seen that the laser intensity distribution was very symmetrical and near Gaussian-distribution.

4. CONCLUSIONS

A diode-pumped high-repetition-rate A–O Qswitched Nd:YVO₄ quasi-three-level laser at 914 nm was demonstrated in this paper. At 10 kHz, using a plane parallel linear laser cavity with a T = 9% output coupling mirror, a maximum average output power of 2.2 W 914 nm laser was obtained at an incident pump power of 45.3 W, giving an optical conversion efficiency of 4.9% and a slope efficiency of 8.8%. At an incident pump power of 40.8 W, a minimum pulse width of 24 ns and a maximum peak power of 8.0 kW of 914 nm laser was achieved. To the best of our knowledge, this is the highest peak power of 914 nm laser at 10 kHz by far. The highest repetition rate of pulsed 914 nm was up to 100 kHz.

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