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Abstract—High pulse amplitude stability of 0.62% (rms) is achieved at 60 kHz repetition rate in fundamental mode with double-end continuous-grown YVO$_4$/Nd:YVO$_4$/YVO$_4$ composite crystal. The average output power and pulse peak power are 32.9 W and 27.7 kW, respectively, with 19.8 ns pulse width and 548 µJ pulse energy. The pulse amplitude stability is investigated experimentally. The stability gets improved with the decrease of repetition rate and output transmission. From theoretical analysis, the reason of pulse instability at high repetition rates is that the initial population inversion doesn’t saturate and the final population inversion doesn’t approach zero. With the decrease of repetition rate and output transmission, the final population inversion decreases and the interaction between two adjacent pulse periods is weakened. Therefore, pulse stability improves.

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1. INTRODUCTION

Diode-pumped high repetition rate nanosecond acousto-optically Q-switched solid state lasers are widely used in material processing. High pulse stability at high repetition rates is important for applications such as memory yield improvement, via hole drilling, and wafer singulation [1]. High pulse stability is also one of the main technical difficulties in high repetition rate Q-switched lasers. Pulse amplitude instability of 3.3% was achieved at 500 kHz repetition rate and 9.15 W average output power with a grazing-incidence Nd:YVO$_4$ laser [2]. 5% (rms) pulse amplitude instability was achieved at 200 kHz in a simple one-end-pumped Nd:YVO$_4$ laser with 13.8 W average power [3]. 4% (rms) pulse amplitude instability from 60 kHz to 500 kHz was measured in a double-end-pumped folded-cavity Nd:YVO$_4$ laser with 36 W average power in continuous-wave operation [4]. However, the reason of pulse instability at high repetition rates was not analyzed in these papers.

Nd:YVO$_4$ is widely used for high-repetition-rate short-pulse-width Q-switched operation, thanks to its high stimulated cross section. Thermally bonded Nd:YVO$_4$ with YVO$_4$ in one end or double end are widely investigated recently, aimed to reduce thermal effect, especially the end-surface curvature [4–13]. However, the quality of thermally bonded vanadate crystals is highly dependent on the surface processing quality. They are usually not robust enough for long-time high-power operation. Continuous-grown vanadate crystals are almost as robust as single pure crystal. 10.5 W average power at 100 kHz with 19.8 ns pulse width, and 28.9 W average power at 100 kHz with 12.9 ns pulse width were achieved with one-end grown YVO$_4$/Nd:YVO$_4$ crystals [14, 15].

In this paper, we present a double-end continuous-grown YVO$_4$/Nd:YVO$_4$/YVO$_4$ acousto-optically Q-switched laser with high pulse stability at high repetition rates. Pulse stability at different repetition rates and output transmissions are investigated. In addition, the reason of pulse instability at high repetition rates is analyzed.

2. EXPERIMENTAL SETUP

The experimental setup of the double-end grown YVO$_4$/Nd:YVO$_4$/YVO$_4$ laser is shown in Fig. 1. The a-cut continuous-grown crystal consisted of three sections, a 0.3 at % doped Nd:YVO$_4$ (3 × 16 mm) and two undoped YVO$_4$ (3 × 3 × 2 mm). The end surfaces were coated for high transmission at 808 and 1064 nm. The crystal was adhered in a water-cooled cooper heat-sink by conductive adhesive. All the cavity mirrors were flat mirrors. The dichroic mirrors were coated for high reflection at 1064 nm and anti-reflection at 808 nm at an incident angle of 22.5°. The output coupler was positioned at a distance of $l_1 = 120$ mm from dichroic mirror. The HR mirror was
positioned at a distance of $l_2 = 140$ mm from dichroic mirror, with high reflection at 1064 nm. The core diameter of pump coupling fiber was 0.4 mm, with a numerical aperture of 0.22. The pump light was imaged to a spot of 0.8–0.9 mm diameter in the crystal by coupling lens. The maximum output power of the fiber-coupled laser diodes was 45 W at 808 nm. ANEOS acousto-optical Q-switch with 40 MHz RF frequency was set in the cavity. The measurement instruments included a COHERENT power meter (model: LM-200), a THORLABS photo detector (model: DET210), and a YOKOGAWA oscilloscope (model: DL7200).

3. EXPERIMENTAL RESULTS

Figure 2 shows the average output power as a function of transmission of output coupler, with 36.5 W incident pump power at each end of the crystal. The RF off time was set 1 $\mu$s at different repetition rates. Maximum cw power of 35.9 W was achieved with 50% output coupler. The corresponding optical efficiency was 49.2%. The beam quality factor $M^2$ was smaller than 1.3 with output transmissions higher than 35%. The $M^2$ was smaller than 1.5 with output transmissions from 20 to 35%. With pump power higher than 36.5 W, the beam quality began to degrade. The double-end continuous-grown YVO$_4$/Nd:YVO$_4$/YVO$_4$ composite crystal is robust for industrial application. After more than 300 h operation, the laser didn’t show any obvious power degradation till now.

Figure 3 shows the pulse width as a function of output coupler transmission with the same pump condition and cavity length. Minimum pulse width was generated with 50% output coupler. The pulse width increased linearly with the decrease of output transmission lower than 50%. It kept almost unchanged for output transmissions higher than 45%. The pulse width increased linearly with the increase of pulse repetition rate. For example, it increased from 19.8 to 29.3 ns as repetition rate increased from 60 to 100 kHz, with 40% output transmission.

The pulse amplitude stability degraded with the increase of output transmission and repetition rate, as shown in Fig. 4. 100 pulses were collected to compute