High repetition rate 880 nm diode-directly-pumped electro-optic Q-switched Nd:GdVO₄ laser with a double-crystal RTP electro-optic modulator

Yong-Ji Yu, Xin-Yu Chen, Chao Wang, Chun-Ting Wu, Miao Yu, Guang-Yong Jin*

Jilin Key Laboratory of Solid Laser Technology and Apply, School of Science, Changchun University of Science and Technology, Changchun 130022, China

1. Introduction

High repetition rate short pulse compact solid state 1.06 μm lasers pumped by laser diode arrays (LDAs) are promising and compelling in various fields such as laser ranging, spaceborne lidar, micro-machining, medical treatment, non-linear optics and so on [1–3]. High repetition rate (≥100 kHz) operation can be achieved by Q-switching, especially actively Q-switching, due to its stable pulse energy and low temporal jitter at high repetition rates. Active Q-switching mainly contains two commonly used Q-switch modes, acousto-optic (AO) Q-switch [4–6] and electro-optic (EO) Q-switch [7–9]. The AO Q-switched laser has the feature of high repetition rate (normally can reach 200 kHz), but it is limited in many fields due to its tendency to produce long pulse (typically several tens to one hundred nano-seconds). Compared to AO Q-switch, EO Q-switch can overcome the shortcomings of AO Q-switch, and get stable short pulses due to its fast loss change. But the EO Q-switch requires very high voltage driver; this leads the high repetition rate is difficult to obtain. In recent years, with the development of new types of electro-optic crystals (such as β-BaB₂O₄ (BBO) and La₃Ga₅SiO₁₄ (LGS), RTP), the repetition rates of EO Q-switched solid state lasers have been improved significantly [10–13].

In 2003, Du et al. reported a 50 kHz EO Q-switched slab Nd:YVO₄ laser with the shortest pulse width of 11.3 ns and the maximum average output power of 103 W by using a BBO Pockels cell [10]. This is the highest repetition rate reported on an EO Q-switch using BBO crystals. In 2010, Tang et al. configured a 6.2 W, 9.1 ns EO Q-switching Nd:YVO₄ laser at 30 kHz by using an LGS electro-optic modulator [11]. This is the highest repetition rates of all reported on an EO Q-switch using LGS crystals. The operation-repetition-rate all EO Q-switched lasers mentioned above were less than 100 kHz, limited by the electro-optic crystals properties. Compared with BBO and LGS crystals, RTP crystal stands out due to its ability to achieve amplitude modulation at an extremely high repetition rate because of its larger electro-optic coefficients (RTP: r₁² = 23.6 pm/V, BBO: r₂² = 2.2 pm/V, LGS: r₁₁ = 2.68 pm/V), lower half-wave voltage, high damage threshold (1.8 GW/cm² for 10 ns pulses at 1.06 μm), hydrolysis-repellent, and absence of piezoelectric ringing [12]. Recently, based on this RTP crystal, a few hundred kilohertz EO Q-switched lasers have been reported. In the 2012, our group investigated the performance of 808 nm diode-end-pumped EO Q-switched AFB composite Nd:YVO₄ laser based on a double-crystal RTP electro-optic modulator [13]. The highest repetition rate could reach 200 kHz with the pulse width of 16.65 ns, and the maximum average output power was 11.8 W, corresponding to an optical conversion efficiency of 43.7%. Because of the laser-induced thermal effect, the experimental results show that the average output power will be saturated and the pulse width will be broadened under high repetition rate Q-switched operation. In order to further promote pulse repetition rate and maintain a narrow pulse width and high optical–optical conversion efficiency, it is essential to take measures to control the thermal effect. Direct pumping has been approved to be an efficient scheme because...
exciting Nd\(^{3+}\) ions from the ground-state (\(^{4}I_{9/2}\)) directly to the upper lasing level (\(^{4}F_{3/2}\)) without the relaxation process of \(^{4}F_{3/2} \rightarrow ^{4}F_{3/2}\) could diminish the quantum defect and heat generation effectively. Compared with Nd:YVO\(_4\), Nd:GdVO\(_4\) crystal has better thermal properties. The thermal conductivity along the direction of (110) (about 11.7 W m\(^{-1}\) K\(^{-1}\) at 300 K) is about two times higher than that of Nd:YVO\(_4\) \([14,15]\). Besides these, compared with traditional 808 nm, although the pumping of Nd:GdVO\(_4\) crystal at 880 nm has a lower absorption cross section \((\sigma_{a}=2.7 \times 10^{-19}\text{cm}^2@808\text{nm}\text{and }\sigma_{a}=5.2 \times 10^{-19}\text{cm}^2@880\text{nm})\), it leads to the reduction of quantum defect ratio from 0.24 to 0.17 in the case of \(^{4}F_{3/2} \rightarrow ^{4}F_{1/2}\) emission, which reduces the thermal loading by ~28% at 1.06 \(\mu\text{m}\). Therefore, better results can be expected if directly pumped Nd:GdVO\(_4\) is used as the parent pump method of the EO Q-switched laser. In this paper, we demonstrated a high repetition rate EO Q-switched laser with a double-crystal RTP electro-optic modulator by 880 nm diode-directly-pumped AFB composite Nd:GdVO\(_4\) crystal for the first time. The stable working range of the laser extends from 10 to 280 kHz while the beam quality factor is close to 1.2. The maximum average output power of 11.2 W and the shortest pulse width of 18.4 ns are obtained at 280 kHz with an absorbed pump power of 19.3 W.

2. Experimental setup

The experimental setup is shown in Fig. 1A. JENOPTIK JOLD-30-FC-14 laser diode module by using fiber-coupling was applied as the pumping source in the experiment, which delivered the maximum output power of 30 W at the center wavelength of 880 nm from the fiber bundle ends. The fibers were drawn into round bundles of 200 \(\mu\text{m}\) core radius with the numerical aperture of 0.22. A coupling optics system consists of two identical plano-convex achromatic lenses with focal lengths of 25 mm was employed to re-image the pump beam into the laser medium in the ratio of 1:1. The coupling efficiency was 97%. An AFB composite, a-cut Nd:GdVO\(_4\) crystal was used as the laser medium in our experiments. The AFB composite Nd:GdVO\(_4\) crystal \((3 \times 3 \times 12 \text{ mm}^3)\) consists of three separate sections, a 8 mm 0.5\% Nd\(^{3+}\) doped GdVO\(_4\) crystal being sandwiched by two 2 mm undoped GdVO\(_4\) crystals. Both ends of the crystal were anti-reflection (AR) coated at 880 nm and 1063 nm. In order to decrease the influence of the thermal effects, the crystal was wrapped with indium foil and mounted in semiconductor cooled copper block. A simple plano-convex cavity was set in the experiment. The high reflective (HR) mirror M1 \((R=\infty)\) was AR coated at 880 nm \((R<0.2\%)\) and HR at 1063 nm \((R>99.9\%)\). The output coupler mirror M2 \((R=200\text{ mm})\) has the transmission of 36\% at 1063 nm.

Based on the high repetition voltage-decreased EO Q-switching structure design, the RTP crystal was used as a high repetition EO Q-switch and placed between a polarizer and output coupler mirror M2. The main problem with the RTP crystal is the temperature dependent birefringence, which must be compensated for somehow. In order to compensate for the natural birefringence effect of the RTP crystal as temperature variation, an advantage with the double-crystal structural design has been employed in our experiments. The two x-cut RTPs crystals were equally long and were aligned with their z axes parallel to each other. Furthermore, the x axis of one of the crystals is parallel to the y axis of the other crystal, meaning that the crystals have been rotated 90\(^\circ\) relative to each other. Both double-crystal RTP were used with dimensions of \(3 \times 3 \times 10\text{ mm}^3\), each with mutually perpendicular directions of the y axis and electrodes with quarter-wave voltage of 550 V applied to their optically polished x-z faces. Its driver’s rise and fall times were both less than 10 ns, the pulse delay were set at 1 \(\mu\text{s}\).

3. Results and discussion

With this configuration, when 30 W pump power was supplied to the AFB composite Nd:GdVO\(_4\) crystal, the theoretical focal length was ~72 cm when pump radius was ~200 \(\mu\text{m}\) according to the following formula obtained by Innocenzi et al. \([16]\):

\[
f_i = \frac{\pi K_c \alpha_l w_p^2}{P_{ph}(dn/dT)} \left(\frac{1}{1-\exp(-d_l)}\right)
\]

where \(K_c\) is the heat conductivity, \(w_p\) is the pump radius, \(dn/dT=4.7 \times 10^{-5}\text{K}^{-1}\) is the temperature dependent coefficient of the refractive index, \(\alpha\) is the absorption coefficient of the pump power, it is about 11.2 cm\(^{-1}\) for 0.5\% \([17]\), and \(l\) is the crystal length. \(P_{ph}\) is the fraction of absorbed pump power converted to heat, which is 0.43 in a 1063 nm laser pumped at 880 nm. The cavity length was set to 100 mm, the fundamental mode radius of the laser cavity could be calculated with the ABCD matrix method based on the thermal focal length, resulted in ~200 \(\mu\text{m}\) fundamental mode spot radius of 1063 nm oscillating beam in the Nd:GdVO\(_4\) crystal. Mode volumes of 880 nm pump beam and 1063 nm oscillating beam matched well in the gain medium.

Under the Q-switched operation, the average output power was measured by a laser power meter (L30A-V1, OPHIR Inc.). The Q-switched pulses were detected by a high-speed silicon photodiode (DE10A1M, Thorlabs Inc.) and shown by a digital oscilloscope (TDS2012B, Tektronix Inc.). Fig. 2(a) shows the average output power of the 1063 nm laser and optical-optical conversion efficiency as a function of absorbed pump power at 280 kHz. Correspondingly, Fig. 2(b) shows that the variation of single pulse output energy and pulse width with the absorbed pump power at 280 kHz. The 1063 nm laser threshold was reached at an absorbed pump power as low as 16 W. Following the least-square linear fitting to the data, the rise of average output power, single pulse output energy and optical-optical conversion efficiency versus the absorbed pump power are obviously fast. At the absorbed pump power of 19.3 W.
(or the incident full pump power of 30 W), a maximum average output power of 11.2 W was achieved, corresponding to the optical–optical conversion efficiency of 58% and the slope efficiency of 62.2%. The pulse width decays approximately exponentially as the absorbed pump power increases. The pulse width was 18.4 ns at the maximum absorbed pump power. Fig. 3 shows the pulse series and the typical pulse shape when the maximum absorbed pump power is 19.3 W at 280 kHz, the peak-to-peak fluctuations of pulse amplitude were less than 7% (root mean square, RMS). At the incident full pump power of 30 W, the laser performance at different repetition rates is depicted in Fig. 4. With the increase of the repetition rate, the pulse width was increased and the peak power was decreased. The peak power decreases from 56.3 kW at 10 kHz to 2.2 kW at 280 kHz; corresponding to the pulse width broadening from 6.4 to 18.4 ns. This is mainly due to the low single-pulse gain for Q-switching operated at very high repetition rate. The laser characteristics at 300 kHz were also studied in the experiments. There was a slight broadening of the pulse width compared with that at 280 kHz, but the pulse amplitudes jittered drastically, which indicated the laser pulse repetition rate was not enough to guarantee a stable Q-switched operation beyond 280 kHz.

Moreover, at the maximum absorbed pump power, the beam quality factors were measured by using a laser beam quality analyzer (M2-200S-FW, Spiricon, Inc.) at different pulse repetition rates. The 90/10 Knife-Edge method was used in the measurement. Because of the weak thermal effect with this configuration, the \( M^2 \) factors are almost constant with respect to the pulse repetition rate, as shown in Fig. 5. The beam quality factors of 11.2 W output at 280 kHz were measured as \( M_x^2 = 1.24 \) and \( M_y^2 = 1.26 \) in both horizontal and vertical directions, respectively a near diffraction-limit laser was obtained. The inset in Fig. 5 shows the far-field measured beam cross section distribution of the laser intensity.

4. Conclusions

In conclusion, a high repetition rate EO Q-switched Nd:GdVO\(_4\) laser under direct pumping at 880 nm as theoretically analyzed and experimentally demonstrated. By using a double-crystal RTP EO modulator in the experiment, with an absorbed pump power of 19.3 W and a pulse repetition rates of 280 kHz, the maximum average output power of 11.2 W and the shortest pulse width of 18.4 ns were obtained, corresponding to an optical–optical...
conversion efficiency of 58% and a slope efficiency of 62.2%. The stable Q-switching operation worked at different pulse repetition rate from 10 kHz to 280 kHz while the beam quality factor almost remained constant ($M^2 \approx 1.2$).

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References