Diode-Pumped Passively Q-Switched and Mode-Locked Nd:Lu$_{0.15}$Y$_{0.85}$VO$_4$ Laser with a GaAs Saturable Absorber

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Abstract—By using a-cut Nd:Lu$_{0.15}$Y$_{0.85}$VO$_4$ mixed crystal as laser gain medium, a diode-pumped passively Q-switched and mode-locked (QML) laser with a GaAs saturable absorber in a Z-type folded cavity is demonstrated for the first time. The Q-switched mode-locked laser pulses with about 90% modulation depth are obtained as long as the pump power reached the oscillation threshold. The repetition rate of the passively Q-switched pulse envelope ranges from 50 to 186 kHz as the pump power increases from 0.915 to 6.520 W. Under an incident pump power of 6.52 W, the QML pulses with the largest average output power of 694 mW, the shortest pulse width of 200 ns and the highest pulse energy of 3.73 µJ are obtained. The mode-locked pulse width inside the Q-switched envelope is estimated to be about 275 ps. The experimental results show that Nd:Lu$_{0.15}$Y$_{0.85}$VO$_4$ is a promising mixed crystal for QML laser.

1. INTRODUCTION

All-solid-state passively Q-switched and mode-locked (QML) lasers by using saturable absorber are attractive for their inherent simplicity, low cost, high pulse energy and reliable operation. In the regime of QML, laser pulses are modulated in the Q-switched envelope. Compared with continuous wave (CW) mode-locking lasers, QML lasers are of significantly higher per pulse energy due to the pulses concentrated in Q-switched envelope. QML all-solid-state lasers employing simple solid-state saturable absorber are desirable in nonlinear frequency conversion, precise fabrication of microstructure, surgery and spectroscopy. Especially, in the nonlinear frequency conversion, the transmit efficiency of second harmonic generation is higher in QML operation than that in CW mode-locking operation [1].

Laser material is an essential component of laser system, and it can decide the output power and laser efficiency. Therefore, improving the quality of laser crystals or developing new laser crystals with better laser properties is of great importance. In the last few years, neodymium- (Nd-) doped vanadate crystals have been proved to be excellent laser materials due to their broad absorption bandwidths, large absorption and stimulated emission cross-sections. Some Nd-doped single vanadate crystals, including Nd:YVO$_4$ [2–4], Nd:GdVO$_4$ [5–7], and Nd:LuVO$_4$ [8–11] have already been investigated and attracted much attention for many years. However, their short upper-level lifetimes weaken the ability of storing energy. To overcome this problem, a new class of Nd-doped mixed vanadate crystals such as Nd:Gd$_x$Y$_{1-x}$VO$_4$, Nd:Lu$_x$Gd$_{1-x}$Y$_{0.85}$VO$_4$, and Nd:Lu$_x$Y$_{1-x}$VO$_4$ have been discovered, and their passively Q-switched lasers show that their pulse laser characteristics are much better than those of Nd:YVO$_4$, Nd:GdVO$_4$, Nd:LuVO$_4$ crystals [12–19]. The Nd:Lu$_x$Y$_{1-x}$VO$_4$ crystal is an isomorphism of Nd:YVO$_4$ and Nd:LuVO$_4$ crystals in which some Y (Lu) ions are replaced by a fraction of Lu (Y) ions in Nd:YVO$_4$ (Nd:LuVO$_4$) as Lu$_x$Y$_{1-x}$VO$_4$ crystal. Nd:Lu$_{0.15}$Y$_{0.85}$VO$_4$ has emerged as a promising new laser crystal for diode pumping. Compared with the Nd:LuVO$_4$ ($\sigma_e = 6.9 \times 10^{-19}$ cm$^2$, $\sigma_a = 14.6 \times 10^{-19}$ cm$^2$, and $\Delta\lambda \approx 1.5$ nm) and Nd:YVO$_4$ ($\sigma_e = 5.7 \times 10^{-19}$ cm$^2$, $\sigma_a = 13.5 \times 10^{-19}$ cm$^2$, and $\Delta\lambda \approx 0.8$ nm), the mixed vanadate crystal Nd:Lu$_{0.15}$Y$_{0.85}$VO$_4$ has an even smaller absorption ($\sigma_a$) and stimulated emission ($\sigma_e$) cross-sections at 808 nm and 1.06 µm ($\sigma_a = 1.5 \times 10^{-19}$ cm$^2$, $\sigma_e = 6.4 \times 10^{-19}$ cm$^2$), and even wider fluorescence line-width ($\Delta\lambda \approx 5.1$ nm) [20]. For a mode-locked laser, the mode-locking performance is also ultimately determined by the property of the gain medium. Due to the broad fluorescence line width of Nd:Lu$_{0.15}$Y$_{0.85}$VO$_4$, it is anticipated that better mode-locking performance can be demonstrated. The experimental results show that the passively mode-locked Nd:Lu$_{0.15}$Y$_{0.85}$VO$_4$ laser with a semiconductor saturable absorber mirror (SESAM) has shorter pulse width and higher peak power than those in the passively mode-locked Nd:YVO$_4$ and Nd:LuVO$_4$ lasers with SESAM [20]. Indeed, the good performance in both the actively Q-switched Nd:Lu$_x$Y$_{1-x}$VO$_4$ laser with acousto-optic modulator and the passively Q-
switched Nd:Lu$_{0.15}$Y$_{0.85}$VO$_4$ laser with Cr$^{3+}$: YAG saturable absorber have been demonstrated [21–23]. The QML laser involves two dynamic processes of Q-switching and mode-locking. Because Nd:Lu$_{1-x}$Y$_x$VO$_4$ mixed crystal had much broader fluorescence line-width than either of the single crystals Nd:YVO$_4$ and Nd:LuVO$_4$ due to the inhomogeneous broadening in the fluorescence spectra, it is supposed to have promising properties and more practical applications in the QML laser operation. However, as far as we know, the related QML Nd:Lu$_{0.15}$Y$_{0.85}$VO$_4$ laser has not been reported.

GaAs, due to the virtues of large optical nonlinearity, a high damage threshold and a high linear transmission, is one of the most commonly used saturable absorbers to generate QML laser pulses and has been successfully demonstrated in different laser media [24–28]. So the performance of diode-pumped passively Q-switched and mode-locked (QML) Nd:Lu$_{0.15}$Y$_{0.85}$VO$_4$ laser with GaAs saturable absorber is expected.

In this paper, by using a-cut Nd:Lu$_{0.15}$Y$_{0.85}$VO$_4$ mixed crystal as laser medium, a diode-pumped passively QML laser with GaAs saturable absorber in a Z-type folded cavity has been realized. The stably Q-switched and mode-locked bursts of pulses with nearly 90% modulation depth are obtained. The average output power, the repetition rate and the pulse width of the Q-switched envelope etc. have been measured. The experimental results show that Nd:Lu$_{0.15}$Y$_{0.85}$VO$_4$ is a promising mixed crystal for QML laser.

2. EXPERIMENTAL SETUP

If the photon intensity in the laser cavity is low, GaAs wafer is an effective saturable absorber only for Q-switching. To generate a Q-switched and mode-locked pulse, the intensity fluctuation must be strong. Therefore a cavity with a small beam area in the GaAs wafer is required. In our experiment, a compact Z-type folded cavity is employed, which satisfies the Q-switching and mode-locking conditions. The experimental arrangement is schematically shown in Fig. 1, in which a Z-type folded cavity was designed to provide mode matching with the pump beam and tight focusing on the absorber. The pump source was a commercial fiber coupled laser-diode (FAP system, Coherent Inc., USA) that works at 808 nm. The output pump beam was focused into the laser crystal with a spot size of 440 μm and a numerical aperture (N.A.) of 0.22 by a focusing optical system. The laser resonator was composed of three concave pump mirrors M$_1$, M$_2$, M$_3$ and a flat output mirror M$_4$. The concave mirrors M$_1$, M$_2$, and M$_3$ are all HR-coated at 1064 nm. Their curvature radii are 200, 500, and 200 mm, respectively. The flat output mirror M$_4$ was coated with the partial transmission of 10% at 1.06 μm. The distances M$_1$M$_2$ and M$_2$M$_3$ are 260 and 650 mm, respectively, while the distance between M$_3$ and the output mirror M$_4$ is 100 mm. The whole length of the resonator is 101 cm, corresponding to a roundtrip transmit time of about 6.7 ns. An a-cut Nd:Lu$_{0.15}$Y$_{0.85}$VO$_4$ crystal with a Nd$^{3+}$ doped concentration of 0.38 at % and dimensions of 3 × 3 × 5 mm$^3$ was employed as the laser gain medium. Its both end sides were AR-coated at 1064 nm. The a-cut Nd:Lu$_{0.15}$Y$_{0.85}$VO$_4$ crystal was wrapped with indium foil in order to improve the thermal contact between laser crystal and the copper block, and held in a copper block cooled at 20°C by semiconductor coolers. A 580 μm-thick uncoated GaAs wafer was employed as saturable absorber. The temporal behaviors of the laser pulses were recorded by a TED620B digital oscilloscope (500 MHz bandwidth and 2.5 G/s sampling rate, Tektronix Inc., USA) and a fast Si PIN photodiode with a rise time of about...
A MAX 500AD laser power meter (COHERENT Inc., USA) was used to measure the generated average output power.

### 3. EXPERIMENTAL RESULTS AND DISCUSSION

The threshold pump power for the diode-pumped passively Q-switched and mode-locked \( \text{Nd:Lu}_{0.15}\text{Y}_{0.85}\text{VO}_4 \) laser with GaAs saturable absorber was found to be 633 mW. The average output power with respect to the incident pump power is shown in Fig. 2. The output power increased with increasing the incident pump power and a maximum average output power of 694 mW was obtained under the maximum incident pump power of 6.52 W. Figure 3 shows the relationship between the repetition rates of the passively Q-switched pulses and the incident pump power. As it can be seen from Fig. 3, the repetition rates increased rapidly from 50 to 186 kHz when the incident pump power increased from 0.915 to 6.520 W. The Q-switched pulse energy was estimated from the average output power and the repetition rate, which is shown in Fig. 4. The pulse energy increased with the augment of pump power. The single pulse energy increases from 0.26 to 3.73 \( \mu \text{J} \) as the incident pump power increases from 0.915 to 6.520 W. The pulse width of Q-switched envelope versus the pump power
has been shown in Fig. 5, in which the shortest pulse width of Q-switched envelope 200 ns is obtained at the incident pump power increases from 6.52 W. A typical experimentally measured oscilloscope trace of a train of Q-switched pulses with the repetition rate 186 kHz at the pump power of 6.532 W is presented in Fig. 6, which shows a high stability as the passively QML laser. Figure 7 shows the temporal shape of a singly passively Q-switched pulse envelop, which was recorded at the maximum pump power of 6.52 W.
From Fig. 7, it is found that the passively Q-switched pulse envelop has a temporal duration of about 200 ns. The modulation depth of the mode-locked pulses train is about 90%. The expanded oscilloscope traces of a train of mode-locked pulses are presented in Fig. 8, from which we can find that the mode-locked pulses within the Q-switched envelope are separated by 6.7 ns, which matches exactly with the cavity roundtrip transmit time and corresponds to repetition rate of 148 MHz. With a close observation, the average rise time of the mode-locked pulse is found to be about 1.3 ns. The formula $t_{\text{rise}} = \sqrt{t_{\text{rise}}^2 + t_{\text{probe}}^2 + t_{\text{oscilloscope}}^2}$ describes the relationships among the measured rise time $t_{\text{measure}}$, the real rise time $t_{\text{real}}$ of the pulse, the rise time $t_{\text{probe}}$ of the probe and $t_{\text{oscilloscope}}$ of the oscilloscope employed [19]. The rise time of oscilloscope $t_{\text{oscilloscope}}$ is determined by $t_{\text{oscilloscope}} \times BW = 0.35–0.40$, where $BW$ is the bandwidth of the oscilloscope. The employed oscilloscope in our experiment is with a bandwidth of 500 MHz and the rise time of employed probe is about 1 ns. Using the above formula, the real rise time of the mode-locked pulse is about 220 ps. According to the definition of the rise time and considering the symmetric shape of the mode-locked pulse, we can assume the width of the pulse is approximately 1.25 times more than the rise time of the pulse. Then the duration of the mode-locked pulse is estimated to be about 275 ps.

The experimental results in Figs. 2–7 show that the mixed crystal Nd:Lu$_{0.15}$Y$_{0.85}$VO$_4$ is excellent laser gain medium for the passively QML laser.

4. CONCLUSIONS

In conclusion, a diode-pumped passively QML a-cut Nd:Lu$_{0.15}$Y$_{0.85}$VO$_4$ laser with a GaAs saturable absorber is demonstrated for the first time. The stably QML laser pulses with about 90% modulation depth are obtained as long as the pump power reached the oscillation threshold. The average output power, the repetition rate and the pulse width of the Q-switched envelope etc. have been measured. The experimental results show that Nd:Lu$_{0.15}$Y$_{0.85}$VO$_4$ is a promising mixed crystal for passively QML laser.

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