Improvement of Doubly Q-Switching and Mode-Locking Performance with Nd-Doped Mixed Vanadate Crystals

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Abstract: By using both the single-walled carbon nanotube saturable absorber (SWCNT-SA) and an acousto-optic (AO) modulator, the stably doubly Q-switched and mode-locked (QML) lasers with Nd-doped mixed vanadate crystals have been realized. The doubly QML laser characteristics are measured. The doubly Q-switching and mode-locking performances are found to be greatly improved by use of $Nd:Gd_{0.3}Lu_{0.33}Y_{0.37}VO_4$ incomparison to that achieved with $Nd:YVO_4$, $Nd:LuVO_4$, and $Nd:Lu_{0.2}Y_{0.8}VO_4$. The experiment results show that the $Nd:Gd_{0.3}Lu_{0.33}Y_{0.37}VO_4$ crystal is more favorable than $Nd:YVO_4$, $Nd:LuVO_4$, and $Nd:Lu_{0.2}Y_{0.8}VO_4$ for doubly QML lasers with AO modulator and SWCNT-SA.

Key words: SWCNT-SA, doubly QML laser, mixed vanadate crystal.

1. Introduction

Simultaneously Q-switched and mode-locked (QML) lasers can generate the bursts of ps pulses with the higher peak power than that of CW mode-locked pulses. These kinds of lasers have found wide application in the visible display, the material-processing, nonlinear optics and so on. Diode-pumped passively QML lasers with saturable absorbers can supply this kind of pulses and have the advantages of simplicity, compactness, low cost and high efficiency. Novel saturable absorbers with easy fabrication technology and ultra-fast recovery times are needed for the QML lasers. Recently Single-walled carbon nanotube saturable absorbers (SWCNT-SAs) were used in solid-state lasers owing to their broad wavelength range from 1 to 2 μm, simple and inexpensive fabrication process as well as high speed third-order optical nonlinearity [1]-[5]. The experimental results indicated that SWCNT-SA was excellent saturable absorber for mode-locked lasers. However, the solely passively QML laser with SWCNT-SA has the poor shot-to-shot stability and reproducibility as well as the low controllability for the pulse repetition rate, which can be improved by adding an active modulator into the laser cavity [6]-[9], known as the dual-loss modulations. In these lasers, the repetition rate of the Q-switched envelope is controlled by the active switch while the mode-locked pulses inside the Q-switched envelope depend on both the actively modulated loss and the saturable absorption. Thus the double QML lasers with the active acousto-optic (AO) modulator and SWCNT-SA are worth expecting.

Neodymium-doped vanadate crystals, because of large absorption coefficients and wide absorption bandwidths, have been widely used in diode-pumped cw solid-state lasers. Among of them, Nd:BaYF [10],

$Nd:YVO_4$ [11], and $Nd:GdVO_4$ [12] have been used in diode-pumped solid-state lasers with SWCNT-SA. On the other hand, Too-large emission cross-section and the short fluorescence line widths of vanadate crystals, which limit their energy storage significantly, are serious drawbacks in Q-switching operation regime [13]. In order to improve the performance of lasers, the double-mixed $Nd:Gd_xY_{1-x}VO_4$, $Nd:Lu_xGd_{1-x}VO_4$, and $Nd:Lu_xY_{1-x}VO_4$ crystals have been grown and extensively studied as gain media for all-solid state picoseconds pulse source [13]-[15]. Due to the reduction of the stimulated emission cross-section and the inhomogeneous broadening of the fluorescence line widths, larger pulse energy and shorter pulse width can be obtained in the double-mixed crystals lasers than those in single vanadate crystal lasers. Recently, a new triple-mixed vanadate crystal $Nd:Gd_{0.3}Lu_{0.33}Y_{0.37}VO_4$ has been fabricated [16]. The physical parameters of $Nd:Gd_{0.3}Lu_{0.33}Y_{0.37}VO_4$ were shown in Table 1 in comparison to $Nd:YVO_4$, $Nd:LuVO_4$, and $Nd:Lu_{0.2}Y_{0.8}VO_4$. It can be seen that $Nd:Gd_{0.3}Lu_{0.33}Y_{0.37}VO_4$ has smaller stimulated emission cross-section and broader fluorescence line width which is very importance for shorter pulse and higher peak power in pulsed laser systems. The QML laser involves two dynamic processes of Q-switching and mode-locking. However, the effects of the stimulated emission cross-section and the fluorescence line width on the simultaneously QML lasers haven't been reported as far as we known.

Table 1. Comparison between $Nd:Gd_{0.3}Lu_{0.33}Y_{0.37}VO_4$, $Nd:Lu_{0.2}Y_{0.8}VO_4$, $Nd:LuVO_4$, and $Nd:YVO_4$

Crystals	Fluorescence line widths (nm)	Fluorescence lifetime (μs)	Absorption cross section (cm^2)	Emission cross section (cm^2)
$Nd:YVO_4$	0.8	98	57×10^{-20}	250×10^{-20}
$Nd:LuVO_4$	1.5	95	69×10^{-20}	146×10^{-20}
$Nd:Lu_{0.2}Y_{0.8}VO_4$	5.1	106	15×10^{-20}	76×10^{-20}
$Nd:Gd_{0.3}Lu_{0.33}Y_{0.37}VO_4$	6.2	96	13×10^{-20}	73×10^{-20}

In this paper, by using both the single-walled carbon nanotube saturable absorber (SWCNT-SA) and an acousto-optic (AO) modulator, the doubly Q-switched and mode-locked (QML) lasers with $Nd:YVO_4$, $Nd:LuVO_4$, $Nd:Lu_{0.2}Y_{0.8}VO_4$ and $Nd:Gd_{0.3}Lu_{0.33}Y_{0.37}VO_4$ crystals are realized under the same cavity parameters. The experiment results show that due to broader fluorescence line width of $Nd:Gd_{0.3}Lu_{0.33}Y_{0.37}VO_4$, the doubly QML $Nd:Gd_{0.3}Lu_{0.33}Y_{0.37}VO_4$ laser can generate shorter pulse width and higher peak power in comparison with the $Nd:LuVO_4$, $Nd:YVO_4$, or $Nd:Lu_{0.2}Y_{0.8}VO_4$ lasers.

2. Experiment Setup

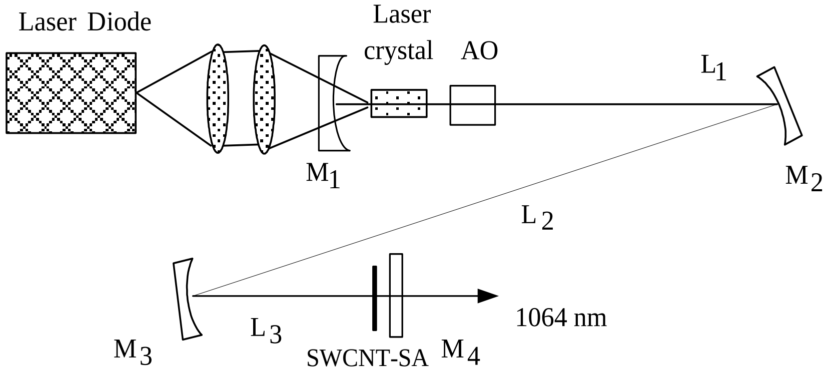

Fig. 1. Schematic diagram of the experimental laser setup.

The laser cavity is shown in Fig. 1 A Z-type folded cavity is employed. Concave mirror M_1 with radius of curvature of 200 mm transmits the pump radiation but reflects the generated laser pulses, functioning as the input mirror. Resonator mirror M_2 and M_3 are two concave mirrors with radii of curvature of 500 and 200 mm, respectively. Both of them are HR coated at 1064 nm. Flat mirror M_4 acts as the output coupler (OC) and its reflectivity is 90 %. The distances between M_1 and M_2 (L_1), M_2 and M_3 (L_2), M_3 and M_4 (L_3)are 26, 66 and 10 cm, respectively.

The pump source employed is a fiber-coupled laser-diode array (Coherent, FAP system) which works at the maximum absorption wavelength (808 nm) of the Nd^{3+} ions. Nd:$Gd_{0.3}Lu_{0.33}Y_{0.37}VO_4$(0.5at.% Nd^{3+}, 3×3×5 mm^3), Nd:$Lu_{0.2}Y_{0.8}VO_4$ (0.5at.% Nd^{3+}, 3×3×5 mm^3), Nd:$LuVO_4$ (0.5at.% Nd^{3+}, 3×3×2.5 mm^3) and Nd:YVO_4 (1.0at.% Nd^{3+}, 3×3×5 mm^3) are used as laser media in our experiment, respectively. They are all cut along the *a*-axis and the 3×3 mm^2faces are polished and antireflection (AR) coated at 808 nm and 1064 nm. To prevent thermally induced fracture and reduce the thermal effect, the gain medium is wrapped with a piece of thin indium foil and inserted into a slot in a water-cooled copper block, keeping at a temperature of 20^{o}C.

An acousto-optic (AO) modulator (The 26th Electronics Institute, Chinese Ministry of Information Industry) is used as active loss modulation. The effective length of AO modulator is 24 mm and both ends are AR coated at 1064 nm. The SWCNT-SA (the quartz substrate coated with SWCNTs/PVA) is used as passive saturable absorption. The SWCNTs were grown by electric arc discharge technique, and the mean diameter is about 1.4 nm.

The pulse temporal profile and repetition frequency are recorded by a Tektronix digital oscilloscope (500 MHz bandwidth and 2.5 Gs/s sampling rate, Tektronix Inc., USA) and a photo detector (New Focus, model 1623). Meanwhile the average output power is measured by a laser power meter (MAX 500AD, Coherent Inc., USA).

3. Experimental Results and Discussions

With an appropriate alignment of the laser cavity, stable QML laser emission was achieved. The doubly QML Nd:YVO_4, Nd:$LuVO_4$, Nd:$Lu_{0.2}Y_{0.8}VO_4$, and Nd:$Gd_{0.3}Lu_{0.33}Y_{0.37}VO_4$ lasers are all studied under the same cavity conditions. The modulation frequency of AO modulator is fixed as 10 kHz.

According to the repetition rate and the average output power, the pulse energy of the single Q-switched envelope versus the incident pump power for the four kinds of QML lasers can be calculated, which are shown with the scattered points in Fig. 2. From Fig. 2, we can see that the pulse energy of the Q-switched envelope almost increases with pump power. At the pump power of 7.09 W, the obtained maximum pulse energy is 39.3 μJ for the double QMLNd:$Gd_{0.3}Lu_{0.33}Y_{0.37}VO_4$ laser, which is higher than that obtained in the double QML Nd:YVO_4 (28.11 μJ), Nd:$LuVO_4$ (31.3 μJ), and Nd:$Lu_{0.2}Y_{0.8}VO_4$ (36.1μJ) lasers. The pulse energy enhancement may result from the smaller stimulated emission cross-section and the broader fluorescence line width.

Fig. 3 shows the pulse width on incident pump power for four kinds of double QML lasers with the squares. From Fig. 3, it can be seen that the double QML Nd:$Gd_{0.3}Lu_{0.33}Y_{0.37}VO_4$l aser can generate shorter pulse than that obtained in the double QML Nd:YVO_4, Nd:$LuVO_4$, and Nd:$Lu_{0.2}Y_{0.8}VO_4$lasers. Fig.4 shows the temporal shape of Q-switched pulse envelope for four kinds of QML lasers at the pump power of 7.09 W. The shortest pulse width of the dual-loss modulated QML Nd:YVO_4, Nd:$LuVO_4$, Nd:$Lu_{0.15}Y_{0.85}VO_4$, and Nd:$Gd_{0.3}Lu_{0.33}Y_{0.37}VO_4$ laser are 140, 100, 90, and 80 ns, respectively. In comparison with the double QML Nd:YVO_4, Nd:$LuVO_4$, and Nd:$Lu_{0.15}Y_{0.85}VO_4$ lasers, the double QML Nd:$Gd_{0.3}Lu_{0.33}Y_{0.37}VO_4$ laser has compressed the pulse width by 43, 20 and 11.1%, respectively. Broader fluorescence line width of laser medium may result in shorter pulse width of Q-switched pulse envelope in QML laser.

According to the above results, the highest pulse energy and shortest pulse width can be obtained for the double QML $Nd:Gd_{0.3}Lu_{0.33}Y_{0.37}VO_4$ laser. However for the QML laser, it is very difficult to directly measure the mode-locked pulse width in the Q-switched envelope even using an autocorrelation. So the mode-locked pulse width can be estimated by the formula [17].

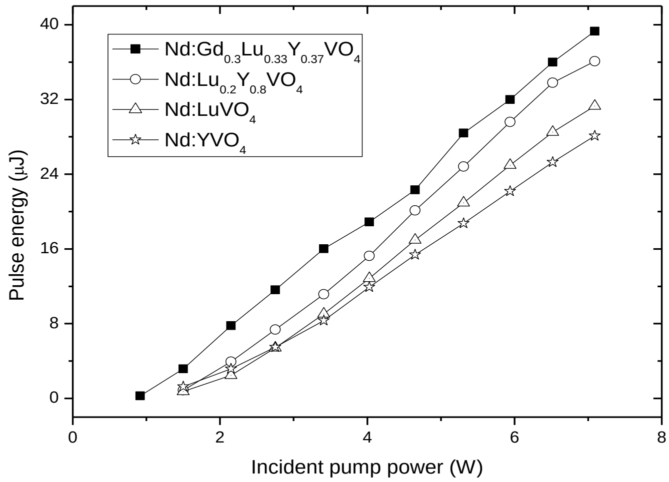

Fig. 2. Pulse energy of the Q-switched envelope versus the incident pump power.

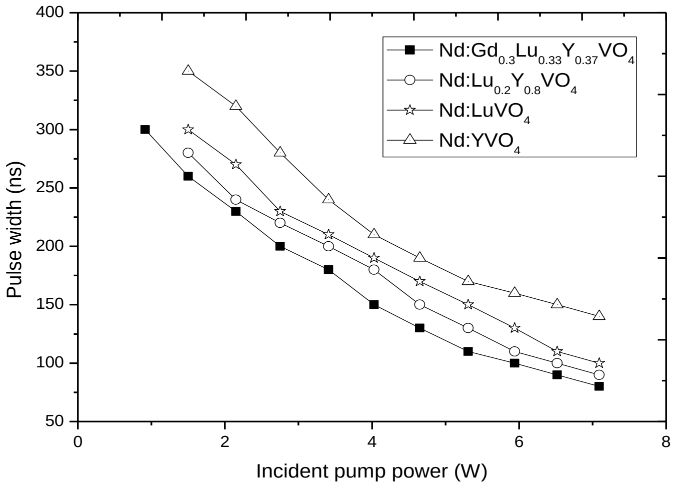

Fig. 3. Pulse width of Q-switched envelope versus incident pump power.

$$t_{real} = \left(t_{measure}^2 - t_{probe}^2 - t_{oscilloscope}^2\right)^{1/2}, \qquad (1)$$

Here, t_{real} real of the pulse, $t_{measure}$ is the measured rise time, t_{probe} is the rise time of the probe and $t_{oscilloscope}$ is the rise time of the oscilloscope. In our experiment, the average rise time of the mode-locked pulse in double QML $Nd:Gd_{0.3}Lu_{0.33}Y_{0.37}VO_4$ laser is measured to be 1.4 ns, which is shown in Fig. 5. The rise time of oscilloscope is 0.8 ns, and the rise time of the probe is about 1 ns. The real rise time of the mode-locked is about 565 ps. Then assuming the width of the pulse is approximately 1.25 times more than the rise time of the pulse, the estimated mode-locked pulse duration is about 706 ps. According to the pulse energy and the mode-locked pulse number inside the Q-switched envelope, the calculated maximum average mode-locked pulse peak power for double QML $Nd:Gd_{0.3}Lu_{0.33}Y_{0.37}VO_4$ laser is 47.3 kW at the pump power of 7.09 W.

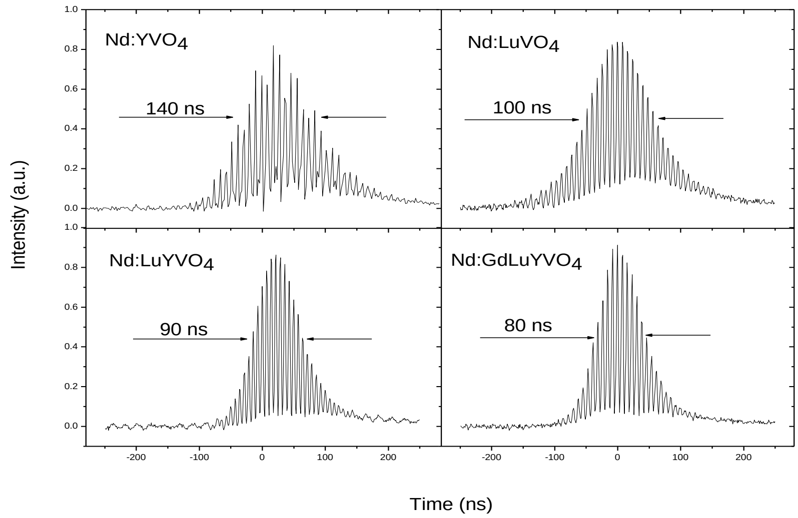

Fig. 4. Expanded temporal shape of a single QML pulse trains at 7.09 W pumping power for $Nd:YVO_4$, $Nd:LuVO_4$, $Nd:Lu_{0.15}Y_{0.85}VO_4$, and $Nd:Gd_{0.3}Lu_{0.33}Y_{0.37}VO_4$.

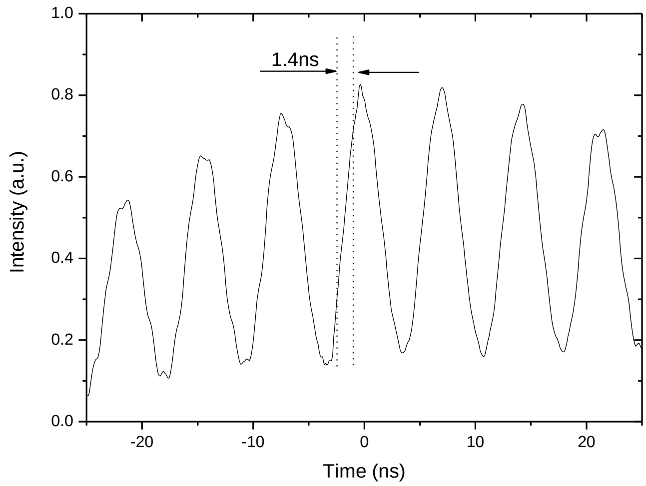

Fig. 5. Expanded oscilloscope traces of a train of mode-locked pulses at the pump power of 7.09 W for $Nd:Gd_{0.3}Lu_{0.33}Y_{0.37}VO_4$.

4. Conclusions

In conclusion, by using both the single-walled carbon nanotube saturable absorber (SWCNT-SA) and anacousto-optic (AO) modulator, the doubly Q-switched and mode-locked (QML) lasers with $Nd:YVO_4$, $Nd:LuVO_4$, $Nd:Lu_{0.2}Y_{0.8}VO_4$ and $Nd:Gd_{0.3}Lu_{0.33}Y_{0.37}VO_4$ crystals have been realized. The experiment results show that the doubly QML $Nd:Gd_{0.3}Lu_{0.33}Y_{0.37}VO_4$ laser can generate shorter pulse width and higher peak power in comparison with the $Nd:LuVO_4$, $Nd:YVO_4$, or $Nd:Lu_{0.2}Y_{0.8}VO_4$lasers. For the QML lasers, broader fluorescence line width of laser medium may result in shorter pulse width and higher peak power of Q-switched pulse envelope.

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