Nd:LuVO$_4$ Laser Passively Mode-Locked by $\chi^{(2)}$-Lens Formation in Periodically-Poled Stoichiometric Lithium Tantalate

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Abstract: Stable mode-locking of a Nd:LuVO$_4$ laser by intracavity second harmonic generation in PPMgSLT nonlinear crystal is demonstrated with maximum achieved average powers of 1.7 W and pulse durations as short as 3.4 ps.

OCIS codes: (140.3530) Lasers, neodymium; (140.4050) Mode-locked lasers; (140.3480) Lasers, diode-pumped.

1. Introduction

In the past decade the orthovanadate crystals TVO$_4$ (T=Y, Gd, Lu) have become one of the most important host materials for the neodymium active ion. The large absorption and stimulated emission cross-sections are properties attractive for the development of efficient diode pumped laser systems. The Nd:YVO$_4$ laser has been widely used both in research and in commercial devices. Another vanadate crystal, Nd:GdVO$_4$, found to be superior to Nd:YVO$_4$ with respect to thermal properties, has also been investigated extensively in continuous-wave (cw), Q-switched, and mode-locked regime of operation. Recently, mixed vanadate crystals Nd:Gd$_x$Y$_{1-x}$VO$_4$ were also studied and found to be superior in the Q-switched regime [1]. The third representative of this family, Nd:LuVO$_4$, is known to possess absorption and emission cross sections higher than Nd:YVO$_4$ and Nd:GdVO$_4$, and also somewhat wider fluorescence emission spectrum (1.5 nm) [2,3], but this material is still not so widely spread. Nowadays, improvements in the growth technology make crystals of Nd:LuVO$_4$ available in dimensions and laser quality that are comparable with those of Nd:YVO$_4$. In this work we apply PPMgSLT for mode-locking of a Nd:LuVO$_4$ laser where the mode-locking mechanism is based on $\chi^{(2)}$-lens formation assisted by the frequency-doubling nonlinear mirror (FDNLM) effect, a hybrid technique recently developed and demonstrated in Nd:YVO$_4$ [4] and Nd:GdVO$_4$ [5] lasers with PPKTP and PPMgSLT nonlinear crystals, respectively.

2. Experimental set-up

The laser cavity is schematically shown in Fig. 1. The active element (AE) was a plane-parallel, 6 mm long, Nd:LuVO$_4$ crystal with 0.4 at. % doping. It was *a*-cut and used for operation in the π-polarization. The end faces were antireflection (AR) coated for minimum losses at the laser wavelength. Nevertheless, the crystal was slightly tilted in order to avoid etalon effects in the laser cavity. It was mounted in a Cu holder whose temperature was stabilized at 25°C by circulating water. The Nd:LuVO$_4$ laser was longitudinally pumped by the unpolarized radiation of a 808 nm laser diode bar coupled into a 400 μm optical fiber (NA=0.22). The output beam from the optical fiber was focused by a 1:1 reimaging unit and delivered onto the Nd:LuVO$_4$ crystal with a spot radius of ~200 μm through the highly reflecting end mirror M1 which transmits the pump radiation (Fig. 1).

The nonlinear crystal (NLC) was PPMgSLT with 1 mol % doping and a thickness of 1 mm along the z-axis. The samples prepared were 5 mm wide and 10 mm long. Both 5×1 mm^2 faces were AR-coated for the fundamental and second harmonic wavelengths. The period (8 μm) was designed for phase-matched second harmonic generation (SHG) at 1064.2 nm and a temperature of 34±1°C. The temperature was adjusted and stabilized through precise control of the temperature of the water circulating through the Cu holder.

The radius of curvature (RC) of the folding mirror M2 (RC= 504 mm), the focal length of the AR-coated intra-cavity lens (80 mm), and the separations given in Fig. 1 were chosen to ensure beam radii of ~80 μm in the nonlinear crystal and ~200 μm in the position of the active element. Plane mirrors with different characteristics were employed as output couplers (OC). The physical cavity length amounted to ~ 1.4 m.

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After an initial alignment of the laser, the position of the intracavity lens was optimized in order to achieve maximum output power in the fundamental transverse mode TEM_{00}, at a fixed distance of ~20 mm between the PPMgSLT crystal and the output coupler. This distance was then varied by translation of the output coupler in order to improve the stability and achieve stable operation in the mode-locked regime using different OCs.

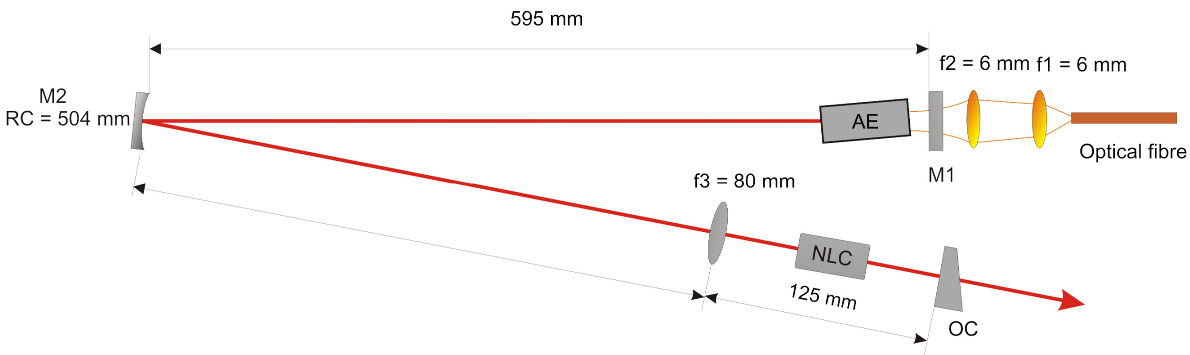

Fig. 1. Experimental set-up of the mode-locked $Nd:LuVO_4$ laser (AE: active element, NLC nonlinear crystal).

3. Results and discussion

Mode-locked operation was studied with three different output couplers. Two of them were highly reflecting at the second harmonic and had transmission of 5% and 20% at the fundamental while the third mirror was highly transmitting at the second harmonic with 5% transmission at the fundamental. Using the last of these mirrors we first estimated the SHG phase-matching temperature for the PPMgSLT crystal when inside the cavity for an output power of ~1 W at the fundamental. The measured value of 47.2°C for maximum second harmonic power corresponds to the temperature of the holder. The deviation from the design temperature of 34±1°C is due to the longer wavelength (1065 nm) of $Nd:LuVO_4$ [3]. Similar temperature measurements were performed also in the passively mode-locked regime and the optimum value for stable operation was in the range 57±2°C depending on the OC used. This corresponds to SHG far from perfect phase-matching, close to the second side maximum of the temperature dependent phase-matching curve.

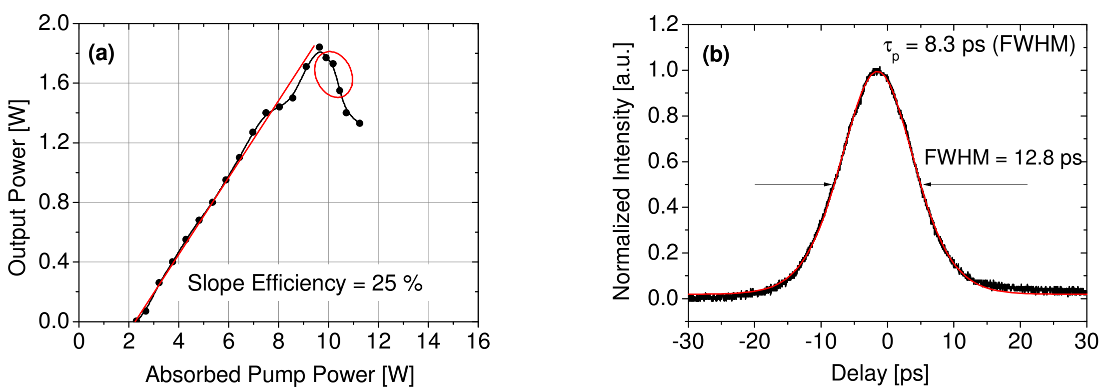

Fig. 2. (a) Input-output characteristics of the $Nd:LuVO_4$ laser and (b) autocorrelation trace and $sech^2$ fit at highest output power.

Stable mode-locking was achieved with both dichroic OCs highly reflecting at the second harmonic. In this case both FDNLM and $\chi^{(2)}$-lens mode-locking processes are simultaneously present. The nonlinear reflectivity of the FDNLM depends strongly on the phase-mismatch and reaches a maximum level when SHG is perfectly phase-matched [4]. On the other side, the cascaded $\chi^{(2)}$-lens is formed only in the presence of phase-mismatch. In order to fully understand the mechanisms of mode-locking, we suppressed the FDNLM effect by using the OC with 5% transmission at the fundamental and high transmission at the second-harmonic, and stable mode-locking operation was still possible. The output power was around 0.6 W under ~7 W of absorbed pump power (see Table 1) and the

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measured pulse duration was 3.4 ps. This is an evidence for the dominant role of the $\chi^{(2)}$-lens formation on the pulse duration.

Maximum output power and efficiency of the mode-locked laser were achieved with the 20% transmittance OC. Figure 2 (a) shows the dependence of the output power on the incident pump power. The laser threshold amounted to 2.3 W of absorbed pump power. Passive mode-locking was possible in the region corresponding to the negative slope parts of the data shown in Fig. 2(a), i.e. between 9.9 and 10.5 W of absorbed pump power.

Table 1. Summary of the mode-locked laser performance of Nd:$LuVO_4$ with three different output couplers.

Output coupler transmittance	5% @ 1064 nm HR @ 532 nm	20% @ 1064 nm HR @ 532 nm	5% @ 1064 nm HT @ 532 nm
Threshold pump power [W]	1.3	2.3	1
Slope efficiency [%]	16	25	12
Absorbed pump power region with stable mode locking [W]	7 – 7.8	9.9 – 10.5	7 – 7.4
Output power [W]	0.68 – 0.55	1.7 – 1.5	0.6 – 0.55
Pulse duration ($sech^2$ shape) [ps]	3.8	8.3	3.4

The highest output power (1.7 W) and slope efficiency (25 %) in stable mode-locked regime were achieved at a pump level of ~10 W. Figure (b) shows the measured autocorrelation trace for this case which leads to an estimation of 8.3 ps for the pulse duration (FWHM assuming $sech^2$ pulse shape). Table 1 summarizes the results with the three different OCs. The shortest pulse duration achieved was 3.4 ps, obtained with the output coupler of 5% transmission at the fundamental and high transmittance at the second harmonic.

It should be emphasized that at present the output level of this mode-locked laser is limited by the achievable output power in the TEM_{00} mode in the cw regime. Power scaling should be possible by redesigning the cavity, which is related to the thermal lens so that the mode-locking region remains in the vicinity of the maximum output power.

4. Conclusion

In conclusion, we reported the first realization of a $\chi^{(2)}$-lens mode-locked Nd:$LuVO_4$ laser using PPMgSLT as an intracavity SHG crystal. Formation of a negative $\chi^{(2)}$-lens in phase-mismatched SHG was identified in the present work as the primary mode-locking mechanism, while the amplitude modulation effect (FDNLM) plays a secondary role, contributing to the starting of the mode-locking process and the long term stability of the laser. Increasing of the intracavity power by using the output coupler with higher reflectivity (95% instead of 80%) at the fundamental improves the pulse shortening capabilities of the system and results in the generation of pulses as short as 3.4 ps.

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