$\chi^{(2)}$-Lens Mode-Locking of a Nd:YVO$_4$ Laser with High Average Power and Repetition Rate up to 600 MHz

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Abstract: We demonstrate $\chi^{(2)}$-lens mode-locking of a diode pumped Nd:YVO$_4$ laser. The output power is 6 W, the pulse duration is 6 ps for repetition rates from 110 MHz up to 600 MHz.
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Mode-locked diode-pumped lasers with high average power (>1 W) and high repetition rate (~1 GHz) have attracted significant attention because of their potential applications, especially in high-capacity telecommunication systems and time-resolved spectroscopy. Semiconductor saturable absorber mirror (SESAM) mode-locking technique has been used already to generate high repetition rate picosecond pulses with duration of 13.7 ps and 21 ps respectively [1,2]. A SESAM with low modulation depth is required in order to prevent Q-switching instabilities, because in fundamental mode-locking regime at certain intra-cavity power increasing the repetition rate leads to reducing the intra-cavity pulse energy [3]. However, utilizing a SESAM with low modulation depth prevents the pulse shortening and self-starting operation of the mode-locking regime. Moreover, the residual absorption of SESAMs can lead to heating or thermal damage of the absorber, especially for operation at high intra-cavity power and high repetition rate. As an alternative to SESAMs, $\chi^{(2)}$-lens mode-locking has been demonstrated with Nd:YVO$_4$ and Nd:GdVO$_4$ lasers emitting output power of several watts with transform-limited pulses [4,5]. In rhis technique two physical processes govern the mode-locking operation: resonator intensity dependent loses due to intra-cavity $\chi^{(2)}$-lens formation and soliton-like pulse shaping due to negative intra-cavity self-phase modulation introduced by phase mismatched SHG. Hence, $\chi^{(2)}$-lens mode-locking enables high power operation, because there is no residual absorption typical for saturable absorbers. Besides, soliton-like pulse shaping substantially reduces the tendency to Q-switching instabilities and supports generation of transform-limited pulses.

In this work we report $\chi^{(2)}$-lens mode-locking of a diode-pumped Nd:YVO$_4$ laser. Stable and self-starting mode-locking operation is achieved in the case of negative intra-cavity self-phase modulation. 6.1 ps transform-limited pulses have been generated with average output power of 6.1 W and repetition rate up to 600 MHz.

The laser design is based on a linear cavity, whose length can vary from 1.5 m to 0.25 m (fig. 1). The active medium is a 9 mm long, *a*-cut Nd:YVO$_4$ crystal with doping concentration of 0.27 at. % Nd^{3+}. It is 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 fiber is focused by a 1:1.5 reimaging unit (F1-F2) and delivered onto the active medium through the mirror M1, which transmits the pump radiation. The pump beam waist is measured to be ≈300 µm in radius and the absorbed pump power is ≈90% of the incident power. The SHG crystal is a periodically-poled 1 mol. % Mg-doped stoichiometric lithium tantalate (PPMgSLT) with thickness of 1 mm along the z axis, length of 10 mm and period of 8 µm. The crystal is mounted in a copper holder, whose temperature is stabilized by circulating water. The phase matching conditions of the PPMgSLT crystal are controlled by the water temperature. The cavity design ensures laser operation in TEM$_{00}$. The thermal lens in the active medium in mode-locking regime is measured (f_{th}≈120 mm). The cavity mode radii are estimated to be ≈100 µm in the SHG crystal and ≈300 µm in the active medium. A plane mirror with transmission of 30% at 1064 nm is employed as an output coupler.

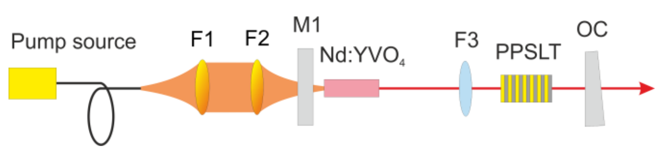

Fig. 1. Laser cavity layout: F1, F2 – pump objective; M1 – highly reflecting convex mirror with radius of curvature RC =413 mm; F3 – focusing lens (f=40 mm); OC – plane output coupler.

$\chi^{(2)}$-lens mode-locking is obtained for cavity lengths of 1.4 m, 0.6 m, 0.3 m and 0.25 m, corresponding to repetition rates (f_{rep}) of 110 MHz, 260 MHz, 500 MHz and 600 MHz respectively (Table 1). The output power (P_{out}) is around 6 W at absorbed pump power (P_{abs}) of ≈26 W. The pulse duration (τ_p) increases for higher repetition rate, or for lower intra-cavity pulse energy (E_{int}). For cavity lengths, shorter than 0.25 m, the intra-cavity power is too low to start and sustain $\chi^{(2)}$-lens mode-locking regime. We can increase the intra-cavity power using lower output coupling. However, at the same pump power multimode operation is observed, which prevents stable mode-locking.

Table 1. Summary of the experimental results, obtained for cavity lengths varying from 1.4 m to 0.25 m.

f_{rep} [MHz]	P_{out} [W]	P_{abs} [W]	E_{int} [nJ]	τ_p [ps]
110	6.3	26	191	4.8
260	6.9	28	88	5.6
500	5.8	25	39	6.1
600	6.1	26	34	6.1

The maximum repetition rate of 600 MHz is achieved for 0.25 m long cavity. The laser threshold (at absorbed pump power of 5 W) depends on the thermal lens power, which governs the stability condition of the laser cavity (fig. 2a). Mode-locking (ML) regime is observed in the pump power range between 26 W and 28 W with maximum output power of 6.1 W. In this range the slope efficiency turns into negative values, because of the non-optimal overlap between the pump waist area and the cavity waist area in the position of the active medium (fig. 2a blue line). The average power in ML is close to the maximum achievable in continuous-wave (CW) operation. This behavior is typical for $\chi^{(2)}$-lens mode-locked lasers [4,5].

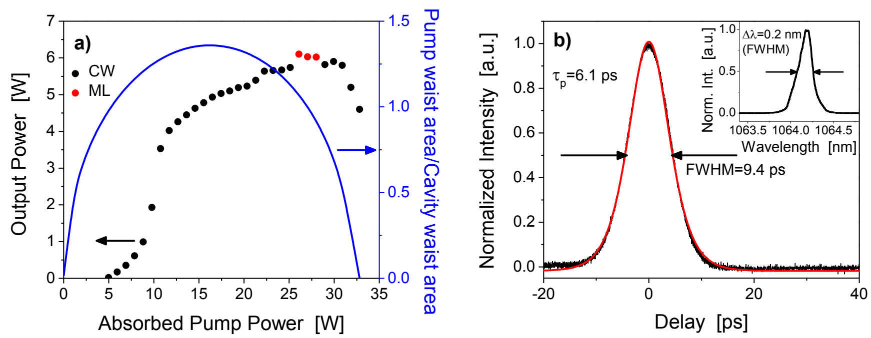

Fig. 2. a) Input-output characteristics of the $Nd:YVO_4$ laser in CW (black dots) and ML operation (red dots); ratio between pump waist area and cavity waist area in the position of the active medium (blue line). b) Autocorrelation curve (black line) and fit assuming $sech^2$ pulse shape (red line); optical spectrum (inset).

The pulse duration (FWHM) is 6.1 ps, derived from the measured autocorrelation curve, assuming $sech^2$-pulse shape (Fig. 2b). The measured optical spectrum has FWHM of 0.2 nm and the laser wavelength is centred at 1064.2 nm (Fig. 2b inset). The time-bandwidth product amounts to 0.32, corresponding to transform-limited pulses for $sech^2$-pulse shape. The mode-locking regime is sustained for several hours with output power fluctuations less than 3%. The measured beam quality factor is M^2_X=1.2 and M^2_Y=1.3 for the horizontal and vertical axes respectively.

In conclusion, we demonstrate a diode-pumped $Nd:YVO_4$ laser mode-locked using $\chi^{(2)}$-lens formation in PPMgSLT SHG crystal. We investigate the mode-locking performance scaling the repetition rate from 110 MHz up to 600 MHz, using the same SHG crystal. We obtain self-starting operation with output power of 6 W and pulse duration of 6 ps at absorbed pump power of 26 W. The maximum repetition rate of 600 MHz is the highest one achieved so far using $\chi^{(2)}$-lens mode-locking. Higher repetition rates (>1 GHz) are expected when using a pump beam with higher brightness.

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References

[1] L. Krainer, R. Paschotta, S. Lecomte, M. Moser, K. J. Weingarten, and U. Keller, "Compact $Nd:YVO_4$ Lasers With Pulse Repetition Rates up to 160 GHz," IEEE Journal of Quantum Electronics **38**, 1334 (2002).

[2] F. Li, K. Liu, N. Zong, B. Feng, J. Zhang, Q. Peng, D. Cui, and Z. Xu, "Compact 7.8-W 1-GHz-repetition-rate passively mode-locked TEM_{00} $Nd:YVO_4$ laser under 880 nm direct-in-band pumping," Opt. Communications **284**, 4619-4622 (2011).

[3] C. Hönninger, R. Paschotta, F. Morier-Genoud, M. Moser, and U. Keller, "Q-switching stability limits of continuous-wave passive mode-locking", J. Opt. Soc. Am. B **16**, 46-56 (1999).

[4] H. Iliev, D. Chuchumishev, I. Buchvarov, and V. Petrov, "High-power picosecond $Nd:GdVO_4$ laser mode locked by SHG in periodically poled stoichiometric lithium tantalate," Opt. Letters **35**, 1016-1018 (2010).

[5] H. Iliev, D. Chuchumishev, I. Buchvarov, and V. Petrov, "Passive mode-locking of a diode-pumped $Nd:YVO_4$ laser by intracavity SHG in PPKTP," Opt. Express **18**, 5754-5762 (2010).