1.34-µm Nd:YVO_4 laser mode-locked by SHG-lens formation in periodically-poled stoichiometric lithium tantalate

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Abstract: Self-starting, steady-state $\chi^{(2)}$–lens mode-locking of a 1.34-µm diode-pumped Nd:YVO_4 laser using intracavity second harmonic generation in PPMgSLT is demonstrated. Pulses as short as 3.6 ps with an average output power of ~1 W are obtained at a repetition rate of 120 MHz.

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

References and links

1. D. A. Armstrong, A. Robertson, N. Langford, and A. I. Ferguson, “1.3-µm diode-pumped Nd:YLF additive-pulse mode-locked laser,” in *Conference on Lasers and Electro-Optics*, Vol. 15 of 1995 OSA Technical Digest Series (Optical Society of America, Washington, D.C., 1995), pp. 344–345.
2. R. Fluck, G. Zhang, U. Keller, K. J. Weingarten, and M. Moser, “Diode-pumped passively mode-locked 1.3-µm Nd:YVO_4 and Nd:YLF lasers by use of semiconductor saturable absorbers,” Opt. Lett. **21**(17), 1378–1380 (1996).
3. S. C. Huang, H. L. Cheng, Y.-F. Chen, K. W. Su, Y. F. Chen, and K. F. Huang, “Diode-pumped passively mode-locked 1342 nm Nd:YVO_4 laser with an AlGaInAs quantum-well saturable absorber,” Opt. Lett. **34**(15), 2348–2350 (2009).
4. I. Buchvarov, G. Christov, and S. Saltiel, “Transient behavior of frequency doubling mode-locker. Numerical analysis,” Opt. Commun. **107**(3-4), 281–286 (1994).
5. S. J. Holmgren, V. Pasiskevicius, and F. Laurell, “Generation of 2.8 ps pulses by mode-locking a Nd:$GdVO_4$ laser with defocusing cascaded Kerr lensing in periodically poled KTP,” Opt. Express **13**(14), 5270–5278 (2005).
6. 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**(6), 5754–5762 (2010).
7. H. Iliev, I. Buchvarov, S. Kurimura, and V. Petrov, “High-power picosecond Nd:$GdVO_4$ laser mode locked by SHG in periodically poled stoichiometric lithium tantalate,” Opt. Lett. **35**(7), 1016–1018 (2010).
8. K. A. Stankov, V. Kubecek, and K. Hamal, “Mode-locking of a Nd:$YAlO_3$ laser at the 1.34-µm transition by a second-harmonic nonlinear mirror,” Opt. Lett. **16**(7), 505–507 (1991).
9. H. Iliev, I. Buchvarov, S. Kurimura, and V. Petrov, “1.3-µm Nd:YVO_4 laser mode locked by cascaded $\chi^{(2)}$ lens formation in periodically-poled stoichiometric lithium tantalate,” Europhoton 2010, 4th EPS-QEOD Europhoton Conference on Solid-State, Fiber and Waveguide Light Sources, Hamburg, Germany, Aug. 29 - Sep. 3, 2010, paper TuP23, Europhysics Conference Abstract Volume 34C.
10. Y. H. Liu, Z. D. Xie, S. D. Pan, X. J. Lv, Y. Yuan, X. P. Hu, J. Lu, L. N. Zhao, C. D. Chen, G. Zhao, and S. N. Zhu, “Diode-pumped passively mode-locked Nd:YVO_4 laser at 1342 nm with periodically poled $LiNbO_3$.,” Opt. Lett. **36**(5), 698–700 (2011).
11. S. V. Tovstonog, S. Kurimura, and K. Kitamura, “High power continuous-wave green light generation by quasiphase matching in Mg stoichiometric lithium tantalate,” Appl. Phys. Lett. **90**(5), 051115 (2007).
12. A. Bruner, D. Eger, M. B. Oron, P. Blau, M. Katz, and S. Ruschin, “Temperature-dependent Sellmeier equation for the refractive index of stoichiometric lithium tantalate,” Opt. Lett. **28**(3), 194–196 (2003).
13. G. D. Boyd and D. A. Kleinman, “Parametric interaction of focused Gaussian light beams,” J. Appl. Phys. **39**(8), 3597–3639 (1968).

1. Introduction

In the last decade, there has been growing interest in steady-state passive mode-locking of diode-pumped Nd-lasers operating on the $^4F_{3/2} \rightarrow {}^4I_{13/2}$ transition around 1.3 µm. Such laser sources could be useful for a number of applications in semiconductor industry, telecommunications and medicine. The first passive, steady-state mode-locking technique

#149601 - $15.00 USD Received 21 Jun 2011; revised 6 Sep 2011; accepted 6 Sep 2011; published 20 Oct 2011

transferred from lamp-pumped to diode-pumped 1.3 µm Nd-lasers was additive mode-locking but this is a complex approach employing single-mode fibers in a coupled cavity and locking electronics [1]. Presently, the much simpler for realization semiconductor saturable absorber mirror (SESAM) mode-locking is widely used near 1 µm but the spectral region around 1.3 µm is problematic because of difficulties in the fabrication process and damage resistivity. With increasing the operating wavelength, technical and engineering problems occur, generally limiting the optical quality of the SESAMs. In fact, each SESAM is designed and fabricated to operate only at a specific wavelength and it is difficult to optimize its modulation depth independently of the nonsaturable losses. The first demonstration of continuous-wave (CW) SESAM mode-locking of a Nd-laser operating near 1.3 µm was in 1996 [2]. In that work, stable mode-locked operation of Nd:YVO_4 and Nd:YLF lasers was reported, with relatively low output powers of 50 and 130 mW, respectively. Pulse durations as short as 4.6 ps in the case of Nd:YVO_4 and 5.7 ps in the case of Nd:YLF were achieved. Subsequently, few other groups have reported on mode-locked operation of 1.3 µm Nd-lasers by different types of SESAMs, basically trying to improve the performance in terms of average output power and long term stability. The highest average output powers (1.05 W at a repetition rate of 152 MHz) were demonstrated only recently [3], with an AlGaInAs based SESAM, however, the pulse duration from this Nd:YVO_4 laser amounted to 26.4 ps.

In this work we investigate an alternative passive mode-locking technique based on second-order nonlinearity inside the laser cavity which utilizes negative $\chi^{(2)}$-lens formation in a second-harmonic generation (SHG) crystal assisted by the nonlinear reflection of the so-called Frequency Doubling Nonlinear Mirror (FDNLM). The FDNLM itself consists of the SHG crystal and the output coupler with partial reflection at the fundamental wave and total reflection at the second-harmonic (SH) wave, respectively, and the dispersive medium between them [4]. This approach is generally free of spectral limitations and absorption problems, and enables easier power scaling to the multi-watt level. The same technique has been previously used for mode-locking of Nd-lasers emitting at 1.06 µm [5–7]. Passive mode-locking of a 1.3 µm Nd-laser using only the FDNLM technique was first demonstrated in the non-stationary regime with pulsed (lamp-) pumping [8]. In the present work, which is an extension of a preliminary conference report [9], not only steady-state mode-locking is achieved but a qualitatively different approach is applied because in contrast to the FDNLM mechanism working alone, the SHG takes place far from perfect phase-matching. More recently, mode-locking of the 1.3 µm transition in Nd:YVO_4 was studied also by others [10], but their work also relies on the FDNLM alone.

The negative $\chi^{(2)}$-lens formation, as a primary mode-locking mechanism utilized in the present work, is quite promising for scaling the average and peak power because the associated single pass intracavity SHG conversion efficiency is rather low (<1%) while any damage related problems in a nonlinear crystal as well as thermal instabilities of the SHG process are normally related to the power level of the SH. Moreover, the FDNLM used as a passive mode-locking mechanism leads to several times longer pulse durations in comparison to $\chi^{(2)}$-lens mode-locking, as previously demonstrated in a 1.06 µm Nd-laser [6]. Here we demonstrate stable steady-state mode-locking of a diode-pumped Nd:YVO_4 laser operating at 1.342 µm with pulse durations as short as 3.6 ps and an average output power of ~1 W, close to the maximum value for CW TEM_{00} operation of the laser. In comparison to previously reported results [2,3,10], for the first time high average powers and short pulse durations are simultaneously available from a passively mode-locked 1.3-µm diode pumped laser source.

2. Experimental set-up

The laser cavity is schematically shown in Fig. 1. The laser crystal (LC) is a 9 mm long, *a*-cut, 1.5°-wedged Nd:YVO_4 with 0.25 at. % doping. The end faces were antireflection (AR) coated for minimum losses at the laser wavelength. The LC was mounted in a Cu holder whose temperature was stabilized at 25°C by circulating water. The 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

#149601 - $15.00 USD Received 21 Jun 2011; revised 6 Sep 2011; accepted 6 Sep 2011; published 20 Oct 2011

reimaging unit and delivered onto the LC through the plane end mirror M, which is transmitting for the pump radiation (Fig. 1).

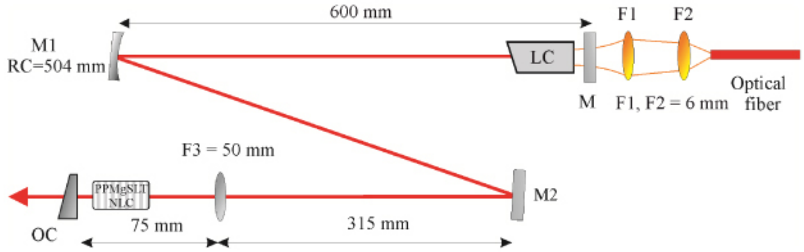

Fig. 1. Schematic of the laser cavity: F1, F2 - pump objective, LC - Nd:YVO_4 laser crystal, M, M1, M2 - highly reflecting mirrors, RC - radius of curvature, F3 – AR-coated focusing lens, NLC – nonlinear crystal, OC - output coupler. The physical cavity length amounts to 1.23 m.

The nonlinear crystal (NLC) is 1-mm-thick periodically-poled 1 mol. % Mg-doped stoichiometric lithium tantalate (PPMgSLT), with dual-band AR-coatings designed for high-power operation [11]. Two samples, 5 mm wide but with different lengths L, 10 mm and 20 mm, where prepared. The period (14.7 µm) was designed for phase-matched SHG at 1.342 µm at a temperature of 461 K (188°C). The NLC was mounted in an oven with high precision (± 0.5K) temperature control.

The radius of curvature (RC) of the folding mirror M1, the focal length of the intracavity lens, and the separations between the cavity elements were chosen to ensure beam radii of ~80 µm in the NLC and ~200 µm in the LC. Plane mirrors with different characteristics were employed as output couplers (OC). Mode-locked operation was studied with two different OCs transmitting 5% and 10% at the fundamental wavelength, both highly reflective at the SH. The Nd:YVO_4 laser operated in π-polarization. The pulse durations were measured using a rapid-scanning autocorrelator consisting of a rotating pair of parallel flat mirrors incorporated in one of the arms of a Michelson-type a Michelson type interferometer. The scaling coefficient defined as ratio between the optical delay and scanning time was 0.016 ps/µs. The autocorrelation signal obtained from non-collinear SHG in a 2-mm thick BBO crystal was detected by a p-i-n photodiode and digital oscilloscope.

3. Experimental results and discussion

The intracavity SH power, normalized by the squared fundamental power in the CW regime, was measured as a function of the crystal temperature (Fig. 2) and showed maximum conversion efficiency at T_{max} = 461.6 ± 0.5 K and a FWHM of ΔT_{FWHM} = 4.6 K. Stable passive mode-locking operation was observed, however, at higher temperatures, at T_{ML} = 467.6 ± 1 K for all output couplers used. This corresponds to far from perfect SHG phase-matching, in the first-order maximum of the temperature-dependent phase-matching curve (see Fig. 2).

A temperature induced phase-mismatch of 4.2 ± 0.6 rad is calculated at 467.5 K using the existing temperature dependent Sellmeier equations for SLT [12]. Nearly the same value, 3.9 rad, is obtained using a value of θ = 0.65 rad/K for the temperature phase-mismatch coefficient derived from fitting the curve in Fig. 2 with theoretically calculated single-pass normalized SHG efficiency as a function of mismatch ($\Delta kL/2$) = $\theta(T\text{-}T_{max})$ where Δk is the wave-vector mismatch [13]. The phase-mismatched SHG introduces $\chi^{(2)}$-nonlinear lens in the laser resonator [5–7]. Operation on the right wing of the phase-matching curve corresponds to a negative $\chi^{(2)}$-lens formation.

The highest CW output power and efficiency were achieved with the OC of 10% transmittance at the laser wavelength and high reflectivity at the SH.When lasing is achieved, the resonator is optimized for high power TEM_{00} mode of operation by adjusting the position of the OC using linear translation stage. Figure 3(a) shows the measured average output power versus incident pump power with the 10 mm long PPMgSLT crystal. The laser threshold is at 3.7 W, while mode-locking is observed in the range between 15.4 and 16.6 W where the CW output power is decreasing with the incident pump power. The maximum output power in the stable mode-locked regime was 1.05 W, obtained at a pump level of 15.4 W. A fast p-i-n photodiode oscilloscope trace of the laser output over a time scale of 30 μs is shown in Fig. 3(b) together with an image of the individual pulses (inset). The amplitude fluctuations are less than 1.5% rms on the microsecond and millisecond time scale.

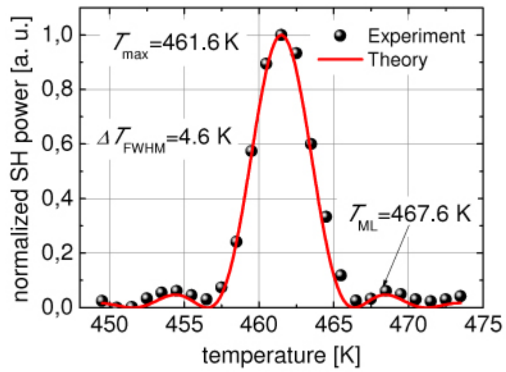

Fig. 2. Normalized single-pass second-harmonic (SH) power as a function of the crystal temperature (*T*) measured with the 10 mm long PPMgSLT crystal in the CW regime and 5% OC that has a leakage of ~1% at the SH.

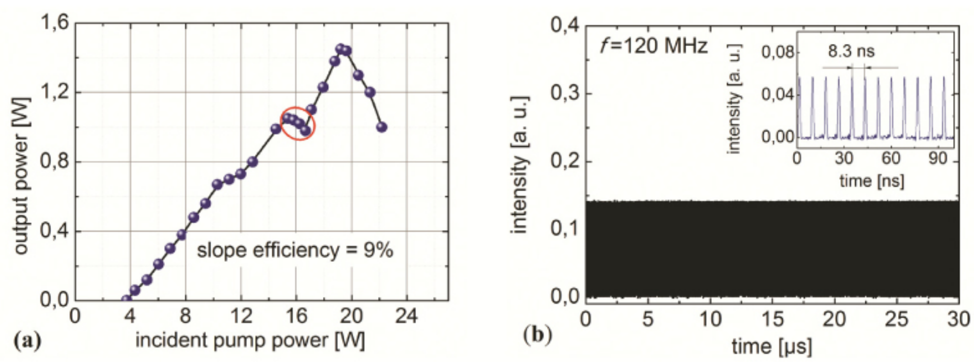

Fig. 3. (a) Input-output characteristics of the $Nd:YVO_4$ laser with the 10% OC and 10 mm long PPMgSLT NLC. The mode-locking range is marked by the red oval. (b) Fast photodiode oscilloscope traces of the mode-locked laser

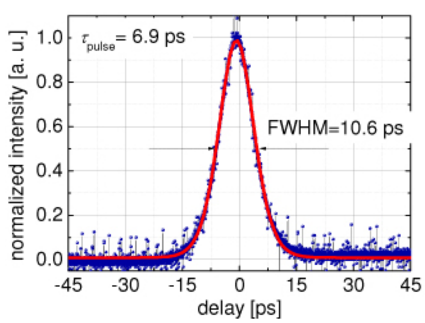

Fig. 4. Autocorrelation trace (blue dots) and fit curve (in red) assuming $sech^2$ pulse shape for the OC with T = 10% providing highest output power.

#149601 - $15.00 USD Received 21 Jun 2011; revised 6 Sep 2011; accepted 6 Sep 2011; published 20 Oct 2011

The performance of the mode-locked laser shows a lot of similarities with the experimental results on mode-locking of the 1 µm transition of Nd-lasers using the same approach [5–7]. Thus, we attribute the main mechanism of mode-locking to the negative $\chi^{(2)}$-lens formation while the amplitude modulation of the FDNLM plays a minor role, contributing mostly to the self-starting. The simulations of our laser cavity using bare-resonator theory indicate that the mode size in the LC is changing upon increasing the thermal lens optical power. It decreases slowly until the thermal lens optical power reaches a value of ~4 Dpt for the chosen resonator design. Additional increase of the thermal lens optical power leads to abrupt increases of the LC mode size. Hence, the laser efficiency is decreasing due to non-optimum overlapping with the pump beam i.e. due to average net-gain decrease which corresponds to the regions of negative slopes of the CW input-output laser characteristics. A negative $\chi^{(2)}$- lens formed in the NLC counteracts the thermal lens and introduces power-dependent effect on the overlap between laser and pump beams, leading to a dependence of the average gain on the intensity

At present the output power level of our mode-locked laser is limited by the achievable output power in the CW TEM_{00} mode of operation, which is determined primarily by the thermal lens effects in the longitudinally diode-pumped Nd-doped LC. Higher CW output powers (up to 1.5 W) were obtained increasing the incident pump power up to ~19 W. Although the laser efficiency starts to decrease again, a second region of stable mode-locking operation was not observed, presumably because of the multimode character of the laser output at this pump level.

Figure 4 shows the measured autocorrelation trace corresponding to maximum output power in the mode-locked regime. The fit, assuming $sech^2$ pulse shape, gives a pulse duration of 6.9 ps (FWHM). Somewhat shorter pulses (5.9 ps) where achieved by replacing the 10% output coupler with one having 5% transmittance at the fundamental and high reflection at second harmonic. The shorter pulse duration obtained in this case is a consequence of the higher intracavity intensity, i.e. stronger $\chi^{(2)}$ –lens effect. However, the reduced transmission of the output coupler also results in approximately 30% decrease in average output power.

The experimental results presented so far were obtained using a 10 mm long PPMgSLT sample. By replacing the NLC with a 20 mm long sample, substantial pulse shortening was observed while the average output power and efficiency remained in the same range. Figure 5 shows the measured average output power versus the incident pump power with the 20 mm PPMgSLT. The observed laser behaviour was similar to the previous case with shorter NLC. Stable mode-locking operation was obtained in the first negative slope region of the oscillator input-output characteristics for pump powers ranging between 12.8 and 13.8 W. The maximum output power in the mode-locked regime reached 0.8 W while the slope efficiency was 11%.

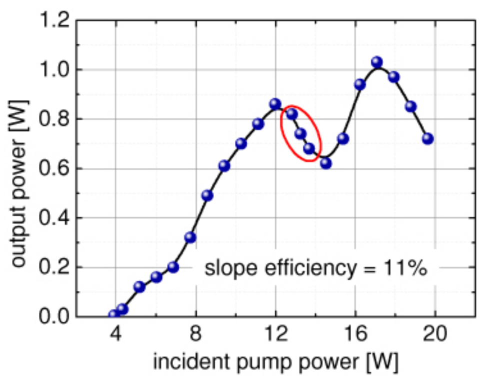

Fig. 5. Input-output characteristics of the $Nd:YVO_4$ laser with 10% OC and 20 mm long PPMgSLT. The mode-locking range is marked by the red oval.

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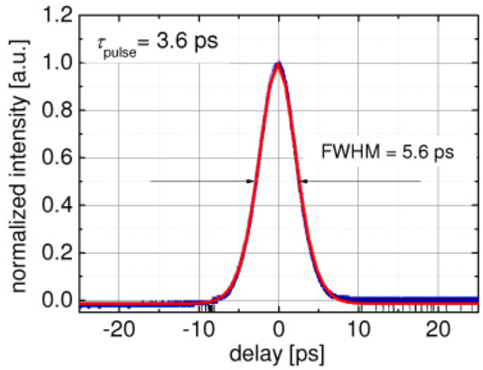

Fig. 6. Autocorrelation trace (blue dots) and fit assuming sech^2 pulse shape (red curve) for 20-mm long PPMgSLT and 10% OC.

The measured autocorrelation trace (see Fig. 6) corresponds to a pulse duration (FWHM) of 3.6 ps assuming sech^2 pulse shape, the shortest pulses achieved so far for this transition of Nd-lasers by any mode-locking technique, approximately three times shorter than ones with pure FDNLM mode-locking recently demonstrated with a similar Nd-vanadate laser [10].

In fact, the proposed technique is quite promising for mode-locking of diode pumped lasers based on narrow-band active media because it relies on a lower order nonlinearity in comparison to the Kerr lens mode-locking technique using $\chi^{(3)}$-nonlinearity, and also because the $\chi^{(2)}$-lens formation can be triggered at relatively low peak intensity. Also, in contrast to the Kerr effect where the resulting nonlinear lens is only positive (i.e. focusing lens), in the case of lens formation based on second order nonlinearity the lens type depends on the sign of the phase-mismatch ΔkL. The latter can be positive which means a negative or diverging lens and negative which means a positive or converging lens. A disadvantage of using second order cascaded nonlinear phase shift compared to the Kerr self-phase modulation for nonlinear lens formation is that it requires SHG crystal and also that it can be saturated. However, the saturation intensity depends on the phase mismatch parameter ΔkL and it increases when moving away from the perfect phase-matching point.

4. Conclusion

In conclusion, we have demonstrated the first realization of a stable and self-starting 1.3 μm mode-locked Nd-vanadate laser using $\chi^{(2)}$-negative lens formation in a PPMgSLT intracavity SHG crystal. The shortest pulse duration obtained is 3.6 ps. Such mode-locking is possible at pump powers corresponding to the negative slope region of the input-output characteristics of the laser in the CW mode of operation. The described technique is applicable in wide spectral regions and could be of special interest in other types of bulk solid-state lasers operating at wavelengths where passive mode-locking techniques are still under development, such as Tm- and Ho-lasers operating near 2 μm. Compared to the FDNLM mode-locking mechanism, the $\chi^{(2)}$-negative lens formation yields much shorter pulse durations.

Acknowledgments

This work has been supported by the Bulgarian Ministry of Education, Youth and Science under grants number VU-L-319/2007 and DO 02/134/2009, by DAAD (Germany) under the PPP program with grant number 50448357, and by JST-CREST research fund in Japan.