High-power picosecond Nd:GdVO$_4$ laser mode locked by SHG in periodically poled stoichiometric lithium tantalate

Hristo Iliev,[1] Ivan Buchvarov,[1,*] Sunao Kurimura,[2] and Valentin Petrov[3]

[1]*Physics Department, Sofia University, 5 James Bourchier Boulevard, BG-1164 Sofia, Bulgaria*
[2]*Advanced Materials Laboratory, National Institute for Materials Science, 1-1 Namiki, Tsukuba 305-0044, Japan*
[3]*Max-Born-Institute for Nonlinear Optics and Ultrafast Spectroscopy, 2A Max-Born-Street, D-12489 Berlin, Germany*
**Corresponding author: ivan.buchvarov@phys.uni-sofia.bg*

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Periodically poled stoichiometric lithium-tantalate is used for mode locking of a diode-pumped Nd:GdVO$_4$ laser by intracavity second-harmonic generation. Stable and self-starting operation is observed achieving average output powers of up to 5 W at a pulse-repetition rate of 107 MHz. The obtained pulse durations range from 6.5 ps at maximum output power down to 3.2 ps at 1.4 W. © 2010 Optical Society of America

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Passive mode locking based on second-order nonlinearity inside the laser cavity is a promising approach for upscaling the power of ultrashort-pulse solid-state lasers. In comparison with the semiconductor saturable absorber mirror (SESAM) technique, the second-harmonic-generation (SHG) approach exhibits no intrinsic power-level limitations, and damage limit 1 order of magnitude higher can be expected while the technological difficulties related to manufacturing high-power SESAMs are avoided [1]. Furthermore, this approach is easily extendable to any laser spectral region. However, the potential of quasi-phase-matched materials related to their higher effective nonlinearity d_{eff} and absence of spatial walk-off seems to not yet have been exploited effectively. Indeed, in diode-pumped mode-locked Nd-lasers, for instance, only periodically-poled KTiOPO$_4$ (PPKTP) crystals have been used up to now, and the highest output power (5.6 W) was achieved at relatively long pulse durations of 20 ps, while the shortest pulses of 2.8 ps were obtained at a modest output power level of 350 mW [2,3]. Although the high d_{eff} of PPKTP supports self-starting mode-locked operation of the laser, the intensity-induced degradation and thermal dephasing will limit its application at higher powers [4]. From direct comparison, it is known that periodically poled Mg-doped stoichiometric lithium tantalate (PPMgSLT), at comparable d_{eff}, shows no photorefraction, detrimental thermal lensing, and insignificant roll-off of the SHG efficiency curve [5]. This indicates that PPMgSLT has strong potential for high-power mode-locking because of its good thermal conductivity.

In this Letter we present the results on passive mode locking of a Nd:GdVO$_4$ laser using PPMgSLT. The obtained output power of 5.0 W is limited by the maximum cw power achievable in TEM$_{00}$ fundamental mode, but the pulse durations are 3 to 6 times shorter than in [2]. The study reveals that two mechanisms are involved in the mode-locking process, and their relative contribution to the pulse shortening depends on the value of the phase-mismatch parameter for SHG in PPMgSLT. The first one relies on the intensity-dependent reflectivity of the frequency-doubling nonlinear mirror (FDNLM), which is composed of the SHG crystal and the output coupler. The second mode-locking mechanism is based on cascaded $\chi^{(2)}$ lens formation in the SHG crystal, and it is identified in the present work as the effect leading to substantial pulse shortening [3].

The laser cavity used is schematically shown in Fig. 1. The active element (AE) is a 9-mm-long, a-cut, 1.5°-wedged and antireflection (AR) coated Nd:GdVO$_4$ crystal with 0.25 at.% doping. The Nd:GdVO$_4$ laser is longitudinally pumped by the unpolarized radiation of a 50 W 808 nm laser diode bar coupled into a 400 μm optical fiber (NA=0.22). The output beam from the optical fiber is focused onto the Nd:GdVO$_4$ crystal to a spot diameter of ~400 μm. The pump power absorption of the AE under lasing conditions is ~86%, optimized by adjustment of the temperature of the laser diode.

The nonlinear crystal (NLC) was PPMgSLT with 1 mol.% doping and a thickness of 1 mm along the z axis. 10- and 20-mm-long samples with an aperture of 5×1 mm^2 were prepared, and both faces were AR coated for the fundamental and the second harmonic (SH). The period (8 μm) was designed for phase-matched SHG at 1064.2 nm and a temperature of 34±1°C. Phase matching was adjusted by the temperature of the NLC, which was stabilized through

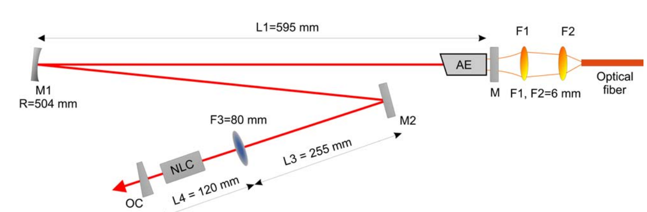

Fig. 1. (Color online) Schematic of the laser cavity: F1, F2, pump objective; AE, Nd:GdVO$_4$ active element; M, M1, M2, highly reflecting mirrors; F3, focusing lens; NLC, PPMgSLT; OC, output coupler. The physical cavity length amounts to 1.4 m.

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precise control of the temperature of the water circulating through the Cu holder. The cavity in Fig. 1 ensures beam diameters of $\sim 300\ \mu m$ in the NLC and $\sim 400\ \mu m$ in the position of the AE.

Mode-locked operation was studied with four different plane output couplers (OCs). Three of them were highly reflecting at the SH and had transmissions of 5%, 20%, and 30% at the fundamental, while the fourth mirror was highly transmitting at the SH with 5% transmission at the fundamental. The measured normalized SH power versus temperature (Fig. 2) shows maximum conversion efficiency at 12°C (holder temperature) and an FWHM of ~4°C for the phase-matching curve. The deviation from the design temperature is mostly due to the shorter wavelength (1063.1 nm) of $Nd:GdVO_4$. Stable passive mode-locking operation was observed, however, at higher temperatures, at 18.5±1°C for all of the OCs used. This corresponds to SHG far from perfect phase matching in the first maximum of the temperature-dependent phase-matching curve. A temperature-induced phase mismatch of ~5.4 rad is calculated at 18.5°C using the temperature-dependent Sellmeier equations for SLT [6]. A similar value of ~5.7 rad is calculated with a value of $\theta = 0.85$ rad/°C for the phase-mismatch coefficient, which is obtained by fitting the curve in Fig. 2 with theoretically calculated single-pass SH for the resonator Gaussian beam versus mismatch $(\Delta k L/2) = \theta \Delta T$ [7].

Maximum output power and efficiency of the mode-locked laser were achieved with the 30% OC. The laser threshold amounted to ~4.7 W. Passive mode locking was possible in two distinctive regions, corresponding to the negative slopes in Fig. 3. The modeling of the field distribution in the resonator shows two stability zones, depending on the thermal lens in the $Nd:GdVO_4$ AE. In the vicinity of the zone limits, the mode size in the AE is changing and the laser efficiency is dropping due to nonoptimum overlapping with the pump beam. Thus a self-starting and stable (against Q switching) mode-locking regime was observed close to the limits of these stability zones, i.e., for pump powers between 16 and 17 W (first region) and between 24 and 27 W (second region) for this OC. The highest output power (5.0 W) and efficiency with respect to the pump power (21.5%) were achieved in the second region at a pump level of 23 W. The corresponding pulse duration of 6.5 ps (FWHM) is deconvolved assuming $sech^2$ pulse shape.

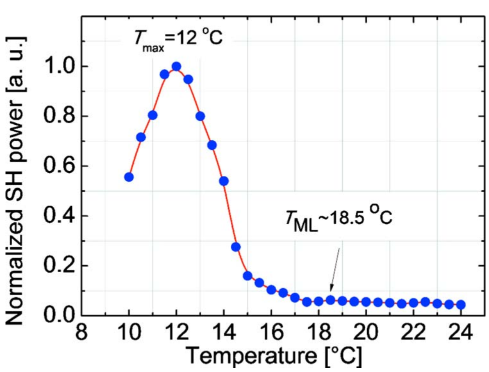

Fig. 2. (Color online) Normalized intracavity SH power divided by the squared fundamental power in the cw regime measured as a function of the crystal holder temperature.

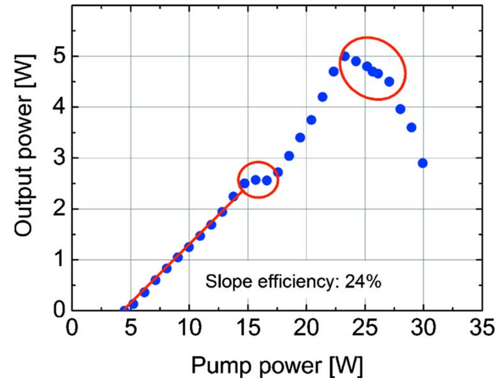

Fig. 3. (Color online) Input–output characteristics of the $Nd:GDVO_4$ laser with the 30% output coupler and the 10 mm PPMgSLT. The mode-locking zones are marked by ovals.

The shortest pulse duration of 3.2 ps was obtained with the output coupler of 5% transmission at the fundamental and high reflectivity at the SH, and using the 20-mm-long PPMgSLT NLC, with maximum output power of 1.4 W.

Stable mode locking was achieved with all the three dichroic OCs with high reflectivity at the SH. In this case both FDNLM and cascaded $\chi^{(2)}$ lens process are simultaneously present. The nonlinear reflectivity of the FDNLM depends strongly on the phase mismatch and reaches a maximum level when the SH is perfectly phase matched. On the other side, the cascaded $\chi^{(2)}$ lens exists only if there is a phase mismatch. To analyze the relative contribution of the two mechanisms to the mode-locking process we studied the dependence of the pulse duration on the temperature of the NLC, i.e., on the phase mismatch. Close to perfect phase matching, the contribution of the FDNLM is relatively large and the pulse duration is around 6 ps. When the temperature of the NLC is away from perfect phase matching, the contribution of the FDNLM is negligible and the pulses get shorter, reaching a minimum around 18°C, then broadening only slightly with increasing temperature, see Fig. 4. We suppressed the FDNLM effect by using the OC with 5% transmission at the fundamental and high transmission at the SH. For both 10- and 20-mm-long NLC, stable mode-locking operation was still achieved. The output power was around 1.5 W under ~25 W of incident pump power, and the measured pulse duration was <4 ps, evidence for the dominant role of the cascaded $\chi^{(2)}$ lens formation on the pulse duration.

The pulse durations given so far refer to the second negative slope region of the input–output characteristics (see Fig. 3). In this region, as a consequence of the higher intracavity intensity, the laser operates with higher output power and shorter pulse duration but also shows stronger tendency to Q-switching instabilities (precise alignment is needed for stable mode-locked operation). In Fig. 5, the measured autocorrelation traces in the first and second regions are compared for the OC with 5% transmittance at

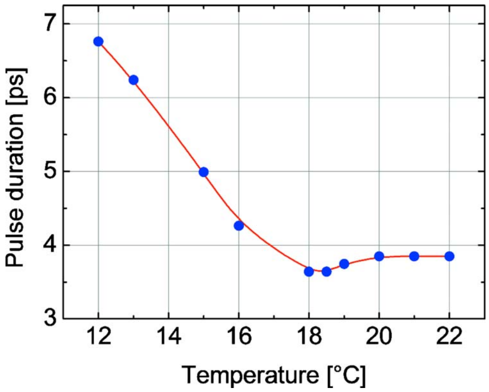

Fig. 4. (Color online) Pulse duration as a function of the NLC temperature, which determines the phase mismatch. The 5% OC, totally reflecting the SH, and the 10-mm-long PPMgSLT are used here.

the fundamental and high reflection at the SH, and the 10-mm-long PPMgSLT. The output power in the first region was around 1 W, and the pulse duration amounted to 5.5 ps. In the second region, the output power was ~1.1 W for a pulse duration of 3.6 ps. These results were confirmed with the 20-mm-long NLC. The resulting sech^2-pulse durations were 5.3 and 3.2 ps, and the output powers were 1.2 and 1.4 W for the first and second regions, respectively.

Difference in the results with the 10- and 20-mm-long PPMgSLT NLCs was basically observed for the OCs with relatively high transmission at the fundamental (20% and 30%). At lower intracavity intensity, the 20-mm-long NLC ensures a stronger cascaded $\chi^{(2)}$ lens, leading to shorter pulses. The performance of the mode-locked laser shows a lot of similarities with the experimental results using PPKTP presented in [3]. Thus we attribute the main mechanism of mode locking to the negative Kerr lens as a result of cascaded $\chi^{(2)}$ nonlinearity while the amplitude modulation effect (FDNLM) plays a minor role, contributing to the self-starting and stabilization of the pulse train. This is confirmed by the fact that group-velocity-mismatch effects (~0.67 ps/mm)

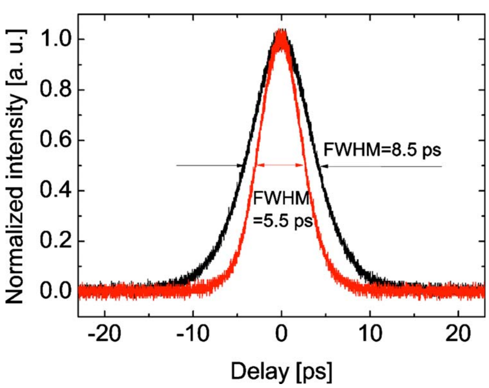

Fig. 5. (Color online) Autocorrelation trace in the first (black curve) and second (gray curve) mode-locking regions.

did not prevent us from obtaining rather short pulses (3 to 6 times shorter than in [2]). Moreover, mode locking was possible using an OC that did not provide a feedback at the SH. Also, 10- and 20-mm-long NLCs resulted in similar pulse durations, although the SHG conversion efficiency is different.

However, there were also qualitative and quantitative deviations from the results described in [3]. We observed two regions of instability and mode locking instead of a single operating point. More important, while in [3] this operation point lies in the region where the output power already decays and the maximum output level in the mode-locking regime was 350 mW of average power, it was possible in our setup to adjust the mode-locking region to an almost maximum pump level, which resulted in >13 times higher average output power. Moreover, at present the output level of our laser is limited by the achievable output power in the TEM_{00} mode in the cw regime, and further scaling seems possible by redesigning the cavity (which is related to the thermal lens [1]) so that the mode-locking region remains in the vicinity of the maximum output power. In fact, the proposed mode-locking technique is quite promising for scaling the average and peak power, because it relies on rather low SHG conversion efficiency (<1%), while any damage related problems in a nonlinear crystal are normally associated with the power level of the SH.

In conclusion, using PPMgSLT for the first time (to our knowledge) for cascaded $\chi^{(2)}$ interaction, creating a negative lens as a mode-locking mechanism in a $Nd:GdVO_4$ laser, resulted in substantial increase of the output power, stable and self-starting operation, and good spatial quality of the output beam. The maximum average output power reached 5 W, and the shortest pulses were 3.2 ps.

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