$Nd:GdVO_4$ laser passively mode-locked by cascaded nonlinearity in periodically-poled lithium tantalate

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Abstract: PPMgSLT is used for mode-locking of a diode-pumped $Nd:GdVO_4$ laser by intracavity SHG. Stable and self-starting operation is observed achieving output powers of up to 4.7 W and pulse durations as short as 3.2 ps.

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

Passive mode-locking based on intracavity $\chi^{(2)}$ nonlinearity is a promising approach for up-scaling the power of ultrashort pulse solid-state lasers which exhibits no intrinsic power-level limitations and an order of magnitude higher damage limit can be expected without the technological difficulties related to manufacturing high-power semiconductor saturable absorber mirrors (SESAMs) [1]. However, the potential of quasi-phase-matched materials related to their higher effective nonlinearity d_{eff} and absence of spatial walk-off seems not to have been exploited effectively, yet. Indeed, in diode-pumped mode-locked Nd-lasers, 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 [2] while the shortest pulses (2.8 ps) were obtained at modest powers of 350 mW [3]. From direct comparison, however, 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 [4], indicating strong potential for high-power mode-locking due to its good thermal conductivity.

Here we describe passive mode-locking of a $Nd:GdVO_4$ laser using PPMgSLT. The obtained output power of 4.7 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 is based on the intensity dependent reflectivity of the “nonlinear mirror” which is composed of the SHG crystal and the output coupler. The second one 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 shown in Fig. 1. The active element (AE), a 9 mm long, *a*-cut, 1.5°-wedged and antireflection (AR) coated $Nd:GdVO_4$ crystal with 0.25 at. % doping, mounted in a Cu holder (temperature: 25°C), is longitudinally pumped by a 50-W 808 nm laser diode bar coupled into a 400 µm optical fiber (NA=0.22). The $Nd:GdVO_4$ laser naturally selects the π-polarization. The pump spot diameter is ~400 µm and the cavity design ensures similar beam diameter in the position of the AE and ~160 µm in the nonlinear crystal (NLC). The NLC is 1 mol % doped PPMgSLT, 1 mm thick along the z-axis. 10 and 20-mm long samples with a period of 8 µm and 5×1 mm^2 aperture with dual AR-coating were prepared. The measured cw SH power versus temperature shows maximum conversion efficiency at 12°C (holder temperature) and a FWHM of ~4°C for the phase-matching curve.

Mode-locked operation was studied with four different plane output couplers (OCs): Three of them were HR at the SH with T=5%, 20% and 30% at the fundamental while the fourth mirror was HT at the SH with T=5% at the fundamental. Stable passive mode-locking operation was observed at 18.5±1°C depending on the OC used, i.e. far from perfect phase-matching, in the first side maximum of the temperature dependent phase-matching curve. A phase-mismatch of ~5.4 rad is calculated at 18.5°C with the temperature dependent Sellmeier equations for SLT [5].

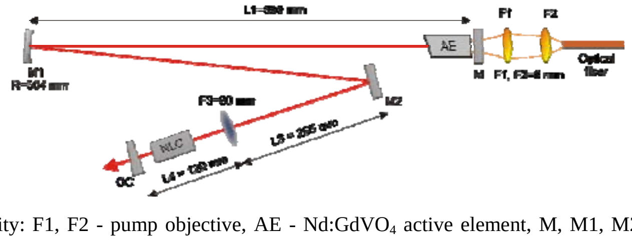

Fig. 1. Schematic of the laser cavity: F1, F2 - pump objective, AE - $Nd:GdVO_4$ active element, M, M1, M2 - highly reflecting mirrors at the fundamental, F3 - focusing lens, NLC - PPMgSLT nonlinear crystal, OC - output coupler. The physical cavity length amounts to 1.4 m.

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Maximum output power and efficiency of the mode-locked laser were achieved with the *T*=30% OC. Passive mode-locking was possible in two distinctive regions, corresponding to the negative slopes in Fig. 2a. The modeling of the field distribution in the resonator shows two stability zones depending on the thermal lens in the Nd:GdVO$_4$ AE. Self-starting and stable (against Q-switching) mode-locking regime was observed close to the limits of these stability zones. The highest output power (4.7 W) and efficiency with respect to the pump power (~19%) were achieved in the second region at a pump level of 25 W. Figure 2b shows the autocorrelation trace, from which a pulse duration (FWHM assuming sech^2 pulse shape) of 6.5 ps is deconvolved.

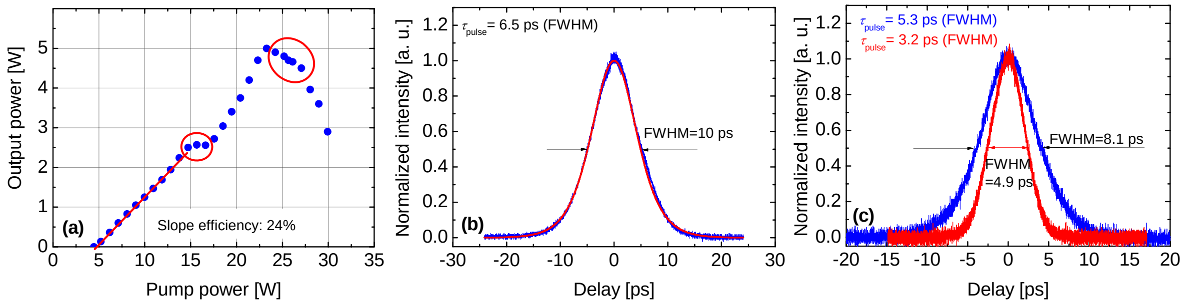

Fig. 2. Input-output characteristics of the Nd:GdVO$_4$ laser with the *T*=30% output coupler and 10-mm long PPMgSLT (a), and autocorrelation trace (blue) and fit assuming sech^2 pulse shape (red) at highest output power (b). Autocorrelation function in the first (blue curve) and second (red curve) mode-locking region obtained with the *T*=5% output coupler highly reflecting at the SH and the 20-mm long PPMgSLT sample..

Stable mode-locking was achieved with all the three dichroic OCs with HR at the SH. In this case both "nonlinear mirror" and cascaded $\chi^{(2)}$ lens process are simultaneously present. Close to the temperature corresponding to perfect phase-matching, the contribution of the "nonlinear mirror" is relatively large and the pulse duration is around 6 ps. At higher NLC temperatures, the pulses get shorter, reaching a minimum around 18°C, then get slightly broader with increasing temperature. We suppressed the "nonlinear mirror" effect by using the OC with *T*=5% at the fundamental and HT at the SH. For both 10 and 20 mm long NLC, stable mode locking operation was still achieved, with output power ~1.5 W at ~25 W of incident pump power, and pulse duration < 4 ps, an evidence for the dominant role of the cascaded $\chi^{(2)}$ lens formation on the pulse duration. In the second stability zone (Fig. 2a), 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. 2c, the measured autocorrelation traces in the 1st and 2nd region are compared for the OC with *T*=5% at the fundamental and HR at the SH, and the 20-mm long PPMgSLT. The resulting sech^2-pulse duration is 5.3 and 3.2 ps and the output power is 1.2 and 1.4 W for the 1st and 2nd region, respectively.

The main mode-locking mechanism is the negative Kerr lens as a result of cascaded $\chi^{(2)}$ nonlinearity [3] while the amplitude modulation effect ("nonlinear mirror") only ensures self-starting and stabilization. This is confirmed by the fact that group velocity mismatch effects did not prevent us from obtaining rather short pulses. Moreover, mode-locking was possible without feedback at the SH. Also, 10 and 20-mm long NLCs produced similar pulse durations with the main difference (somewhat shorter with the 20-mm NLC) observed for the OCs with *T*=20% and 30% for which the intracavity intensity is lower. In contrast to [3], we observed two regions of instability and mode-locking instead of a single operating point. Moreover, while in [3] this operation point lies in the region where the output power already decays, the mode-locking region in our set-up extended to almost maximum pump level which resulted in >13 times higher average output power. In conclusion, using PPMgSLT for cascaded $\chi^{(2)}$ interaction creating a negative lens in a Nd:GdVO$_4$ laser resulted in stable and self-starting mode-locked operation with good spatial quality of the output and maximum average output powers reaching 4.7 W. The shortest pulses were 3.2 ps.

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