# Passive mode-locking of a $Nd:GdVO_4$ laser by intracavity SHG in periodically-poled stoichiometric lithium tantalate

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**Abstract:** Stable and self-starting mode-locking is achieved by cascaded second order nonlinearity using PPMgSLT nonlinear crystal in a $Nd:GdVO_4$ laser, achieving average powers up to 5.1 W and pulse durations as short as 3.8 ps.

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

## 1. Introduction

Cascading second order nonlinearity inside the laser cavity is a promising mode-locking approach for up-scaling the power of ultrashort pulse solid-state lasers. In comparison to the semiconductor saturable absorber mirror (SESAM) technique, this approach exhibits no intrinsic power-level limitations and higher damage limit can be expected while the technological difficulties related to manufacturing high-power SESAMs are avoided [1]. Furthermore, the approach is easily extendable to any spectral region. However, the potential of quasi-phase-matched materials related to their higher effective nonlinearity and absence of spatial walk-off seems not to have been exploited effectively, yet. Indeed, in the case of Nd-lasers for instance, the highest output power in the steady state regime was achieved using periodically-poled $KTiOPO_4$ (PPKTP) in combination with $Nd:YVO_4$ in one version of this approach called "nonlinear mirror" [2]. An output power of 5.6 W for pulse duration of 20-ps was achieved in this work. However, from direct comparison with PPKTP, it is known that periodically-poled Mg-doped stoichiometric lithium tantalate (PPMgSLT), at comparable effective nonlinearity, shows no photorefraction, detrimental thermal lensing and insignificant roll-off of the SHG efficiency curve which suggests that further power scaling should be possible with a higher input [3]. This indicates that PPMgSLT has strong potential for high-power mode-locking because of its good thermal conductivity. In this work we apply PPMgSLT in a $Nd:GdVO_4$ laser to produce similar power levels as in [2], however, at 3 to 5 times shorter pulse duration. In contrast to the amplitude modulation utilized in [2], defocusing cascaded Kerr lensing is identified as the mode-locking mechanism in our laser [4].

## 2. Experimental set-up

The laser cavity is schematically shown in Fig. 1. The active element (AE) was a 9 mm long, *a*-cut, 1.5°-wedged $Nd:GdVO_4$ crystal with 0.25 at. % doping. The end faces were antireflection (AR) coated for minimum losses at the laser wavelength. The laser crystal was mounted in a Cu holder whose temperature was stabilized at 25°C by circulating water. The $Nd:GdVO_4$ laser was 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 was focused by a 1:1 reimaging unit and delivered onto the $Nd:GdVO_4$ 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 $Nd:GdVO_4$ laser naturally selects the $\pi$-polarization and this determines the orientation of the intracavity nonlinear crystal.

The radius of curvature (RC) of the folding mirror M2 (RC=-504 mm), the focal length of the AR-coated intracavity 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.

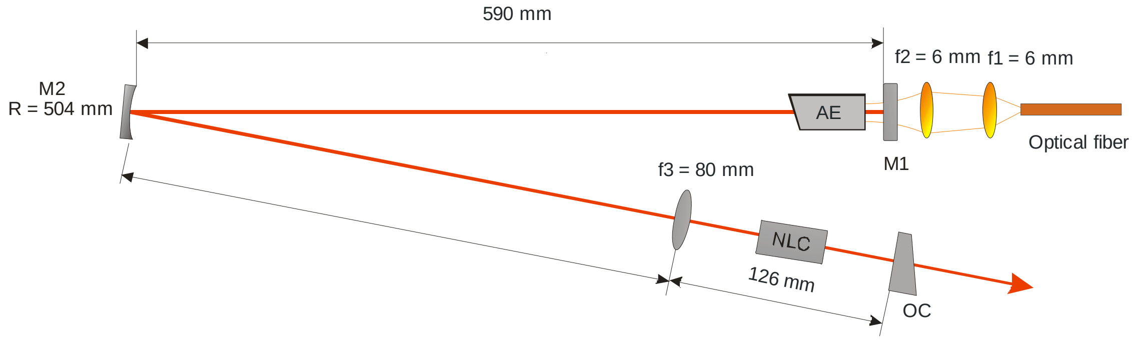


Fig. 1. Experimental set-up of the mode-locked Nd:GdVO$_4$ laser (AE: active element, NLC nonlinear crystal).

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 self-starting operation in the mode-locked regime using different OCs.

## 3. Results and discussion

Mode-locked operation was studied with four different output couplers: Three of them were highly reflecting at the second harmonic and had transmission of 5%, 20% and 30% at the fundamental while the fourth 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 sample when inside the cavity for an output power of ~3 W at the fundamental. The measured value of 10.6°C for maximum second harmonic power corresponds to the temperature of the holder. The deviation from the design temperature of 34±1°C is mostly due to the shorter wavelength (1062.9 nm) of Nd:GdVO$_4$. Similar temperature measurements were performed also in the passively mode-locked regime and the optimum value for stable high-power operation was in the range 21±2°C depending on the OC used. This corresponds to SHG far from the perfect phase-matching, in the second side maximum of the temperature dependent phase-matching curve.

Maximum output power and efficiency of the mode-locked laser were achieved with the 30% transmittance OC. Figure 2 (a) shows the dependence of the output power on the incident pump power. The laser threshold amounted to 4.7 W. Passive mode-locking was possible in two distinctive regions, corresponding to the negative slope parts of the data shown in Fig. 2 (a), i.e. between 16.7 and 20 W of pump power and from 25 up to the maximum of 29 W of incident pump power applied. In the second region, the output power decreased with increasing pump power. We attribute the existence of these two regions to zones of geometrical instability of the resonator, caused by thermal lensing effects in the Nd:GdVO$_4$ crystal. 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 in the 17.6-18.5 W and 26.1-27.5 W ranges.

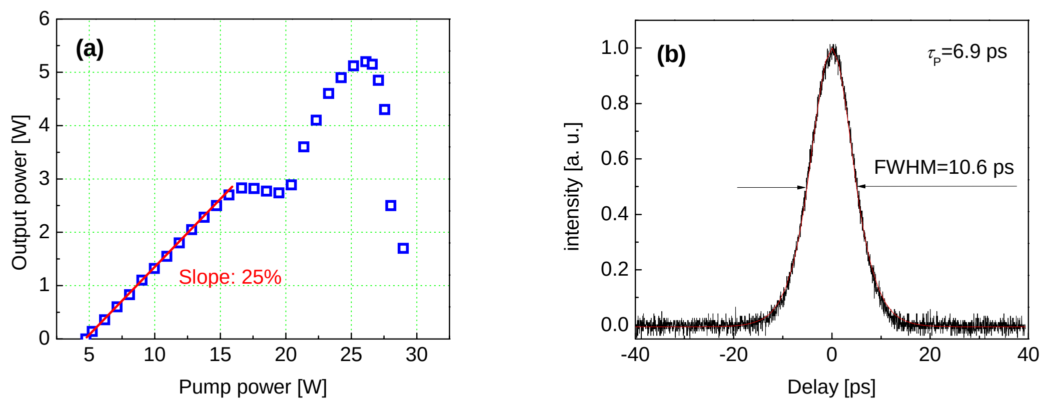


Fig. 2. (a) Input – output characteristics of the Nd:GdVO$_4$ laser and (b) autocorrelation trace and sech$^2$ fit at highest output power.

Table I. Summary of the mode-locked laser performance with four different output couplers.

| Output coupler transmittance | 5%@1064 nm HR@532 nm | 20%@1064 nm HR@532 nm | 30%@1064 nm HR@532 nm | 5%@1064 nm HT@532 nm |
|---|---|---|---|---|
| Threshold pump power [W] | 2.1 | 3.7 | 4.7 | 3.3 |
| Slope efficiency [%] | 7.4 | 23.6 | 25 | 6 |
| Pump power region(s) with stable mode locking [W] | - <br> 18.5 – 21.4 | 16.6 – 17.6 <br> 24.7 – 27.5 | 17.6 – 18.5 <br> 26.1 – 27.5 | - <br> 19.5 – 20 |
| Output power [W] | - <br> 1.0 – 1.05 | 2.4 – 2.5 <br> 4.3 – 2.9 | 2.74 – 2.8 <br> 5.1 – 4.1 | - <br> 1.15 – 1.1 |
| Pulse duration ($sech^2$ shape) [ps] | 3.8 | 5.9 | 6.9 | 5.3 |

The highest output power (5.1 W) and efficiency with respect to the pump power (19.5%) in stable and self-starting mode-locked regime were achieved at a pump level of 26.1 W. Figure 2 (b) shows the measured autocorrelation trace for this case which leads to an estimation of 6.9 ps for the pulse duration (FWHM assuming $sech^2$ pulse shape). Table I summarizes the results with the four different OCs. The shortest pulse duration achieved was 3.8 ps, obtained with the output coupler of 5% transmission at the fundamental and high reflectivity at the second harmonic.

The performance of the mode-locked laser shows a lot of similarities with the experimental results and simulations presented in [4]. 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 (“nonlinear mirror”) plays a minor role contributing only to the self-starting and stabilization of the pulse train. This is confirmed by the fact that group velocity mismatch effects did not prevent us from obtaining rather short pulses (3 to 5 times shorter than in [2]). Mode-locking was possible also using an OC which did not provide a feedback at the second harmonic. Also, direct comparison with a 10-mm long PPKTP in the same set-up resulted in similar pulse durations. In fact, the main advantage of PPMgSLT, besides the higher output power and high spatial quality of the output beam, is the increased stability and self-starting tendency. Moreover, preliminary results with an analogous, but 20-mm long PPMgSLT sample, indicate increase of the output power and even shorter pulses in accordance with the increased cascaded nonlinearity.

However, there were also qualitative and quantitative deviations from the results described in [4]. We observed two regions of instability and mode-locking instead of a single operating point. More important, while in [4] 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 set-up to adjust the mode-locking region to almost maximum pump level which resulted in ~15 times higher average output power. Moreover, at present the output level of our laser is limited by the available pump power and further scaling seems 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, the first realization of cascaded $\chi^{(2)}$ interaction creating a negative Kerr lens as a mode-locking mechanism using PPMgSLT in a $Nd:GdVO_4$ laser resulted in substantial increase of the output power, stable and self-starting operation. The maximum average output power reached 5.1 W and the shortest pulses were 3.8 ps.

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