

Low threshold and high power output of a diode-pumped nonlinear mirror mode-locked Nd:GdVO₄ laser

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Abstract: We demonstrated nonlinear mirror mode-locking of a diode-pumped Nd:GdVO₄ laser by using a 10 mm long KTP crystal. The stable CW mode locking can be reached with the relative low threshold pump power as low as 2.3W. The highest output power of 2.65W at the 10 W pump powers are generated with the 121-MHz repetition rate of pulses. It confirms the excellent laser performance of the Nd:GdVO₄ for high-peak power of the pulse operation.

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OCIS codes: (140.4050) Mode locked laser; (140.3580) Lasers, solid state; (140.3480) Lasers, diode pumped; (190.0190) Nonlinear optics

References and Links

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1. Introduction

All solid-state diode-pumped Nd³⁺ doped picosecond lasers have attracted much attention in various applications such as optical communication, nonlinear optical spectroscopy, optical frequency conversion, microsurgery, and biomedicine. Among the Nd³⁺ doped crystals, Nd:GdVO₄ has become of great interest due to its good optical and mechanical properties. The relatively broader gain bandwidth and the unexpectedly higher thermal conductivity of Nd:GdVO₄ than Nd:YVO₄ makes it favorable for mode-locking with much narrower pulse duration to provide the desirable high-peak power [1].

Intra-cavity saturable absorbers [2, 3] and semiconductor saturable absorber mirrors (SESAM) [4-6] have recently been used for passively mode-locking of Nd:GdVO₄ laser. For generating shorter or femtosecond pulse trains [7], artificial fast saturable absorber utilizing the inherent optical Kerr nonlinearity or self-focusing of the laser crystal has been widely used to self-mode-locked solid-state lasers. However, it is more problematic for Kerr-lens mode-locking of picosecond lasers due to their low peak intensity, which in turn lead to weak nonlinear modulation. The nonlinear mirror mode locking (NLM-ML) provides strong nonlinear loss modulation that was first proposed by Stankov [8]. The NLM-ML consists of a nonlinear crystal placed in front of the output coupler of the laser cavity. The output coupler (OC) provides 100% reflection for the second harmonic wave (SHW) and partial reflection for the fundamental wave (FW). If the SHW experiences an appropriate phase shift with respect to the FW before the second pass through the nonlinear crystal, then the reflected SHW may be completely converted back to the FW. This process acts as a fast saturable absorber, which can compress the FW laser pulse due to less loss (higher conversion into the SHW) in the central part of pulse than the leading and trailing edges at the dichroic OC.

NLM-ML has been experimentally demonstrated in Nd:YAG [9-10] and Nd:YVO₄ [11-14] lasers using various nonlinear crystals, including KTP, PPKTP, and LBO. Recently, we have reported the splitting double pulses in the NLM-ML of the Nd:GdVO₄ laser in the normal dispersion region [15]. Nevertheless, the detail situation of the NLM-ML in Nd:GdVO₄ lasers has not been carefully discussed to our knowledge. In general, Q-switching mode-locking (QML) operation can be observed in a mode-locked laser in use of the saturable absorber before its transition to CW mode-locking (CML). The threshold power for CML against the QML derived by Honninger et al. [16] had been successfully used in the picosecond and femtosecond mode locked lasers with various semiconductor saturable mirrors. Experimentally, high threshold pump powers, such as 9W and 7.5 W for Nd:YVO₄ lasers with 15mm LBO [12] and 3mm KTP [13] nonlinear crystals, were reported to generate stable CML using NLM-ML. To reduce the CML threshold, 10-mm-long type-II KTP or PPKTP were used to generate stable CML at about 4W pumping [13].

In this paper, NLM-ML of diode-pumped Nd:GdVO₄ laser has been achieved by using a 10-mm-long type-II KTP crystal and a OC of 80% reflectivity for the FW. Relatively lower threshold pump power and higher output power for the stable CML are demonstrated in our Nd:GdVO₄ laser.

2. Experiments

The schematic figure-Z laser setup is shown in Fig. 1. A 4x4x8 mm³ a-cut Nd:GdVO₄ crystal (with 0.5% Nd³⁺ concentration) is end-pumped by a fiber-coupled laser diode array (FAP-81-16C-800-I, Coherent Inc.) at 808 nm. The pump beam coming out from the fiber is imaged on the crystal through the 1:1.8 optical imaging accessories (OIA's, Coherent Inc.). Therefore, the radius of the pump beam (W_p) in the gain medium is about 225 μm , which is slightly larger than the estimated radius of the cavity mode (W_g) at the gain medium (about 210 μm by using the ABCD law and considering the thermal lensing effect in the Nd:GdVO₄ crystal). The laser crystal and KTP was wrapped with indium foil and mounted in a water-cooled copper block where the water temperature was maintained at 15 °C. One side of the Nd:GdVO₄ crystal is high-reflection (HR) coated at 1064 nm and anti-reflection (AR) coated at 808 nm pumping wavelength. The other side of the crystal with 2° wedge is AR coated at 1064 nm. The laser cavity consists of two concave mirrors M_1 (the radius of curvature, $R=500$ mm) and M_2 ($R=200$ mm), and a dichroic OC with reflectivity of 80% at 1064 nm and high reflectivity at 532 nm. The total length of the laser is 123 cm, with $l_1=30.5$ cm (the distance from the laser crystal to M_1), $l_2=80.5$ cm (the distance between two curved mirrors M_1 and M_2), and $l_3=11$ cm (the distance from M_2 to OC). A 10-mm-long type-II KTP crystal was antireflection-coated at both end faces for wavelengths of 1064 nm and 532 nm and was placed very close to the dichroic OC for SH generation.

The output power of the Nd:GdVO₄ laser were measured by a power meter (Scientech 365) for both CW and ML states. We used the beam analyzer (WinCamD) to observe the output beam pattern. The leakage radiation reflected from the wedged facet of the laser crystal was detected by a high speed InGaAs detector (Electro-Physics Technology ET 3000) that was connected to the oscilloscope (LeCroy LT372, bandwidth 500MHz) and the RF spectrum analyzer (Hewlett Packard 8560E). A noncollinear autocorrelator with the 1-mm thick type-I BBO, and an optical spectrum analyzer (Ando-AQ6315A) with resolution of 0.01 nm were placed outside the OC to measure the puleswidth and optical spectrum. According to the theory of NLM-ML proposed by Stankov [8], a phase change of $-\pi$ between FW and SHW is needed before the second pass through the nonlinear crystal. Therefore, we adjusted the phase by changing the distance between the nonlinear crystal and the dichroic mirror, which resulted in the dispersion of FW and SHW in the air medium to get the back conversion. Initially, the flashing green light was observed to signal the onset of the nonlinear mode coupling. After slightly detuning the location of KTP, CML pulse trains with linearly polarized and the pure TEM₀₀ output mode with radius about 1.5 mm can be obtained. By further changing the distance between KTP and OC slightly, the phenomena of multiple pulsing and harmonic mode locking can be observed.

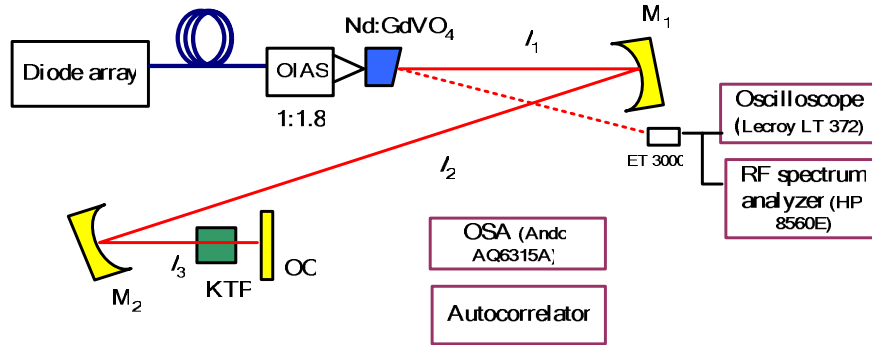


Fig. 1. Schematic diagram of the diode-pumped nonlinear mirror mode-locked Nd:GdVO₄ laser. M_1 and M_2 are folding mirrors and OC is the output coupler.

3. Results and discussion

Figure 2 shows the output power versus the pump power without and with the KTP insertion. The threshold pump power (P_p) of 1.4 W for the CW lasing with KTP insertion (red squares) is slightly higher than that of 1.2 W for CW lasing without KTP insertion (black diamonds). The difference between the output powers without (P_o) and with ($P_{o,KTP}$) KTP increases as the pump power increases, and eventually reaches an almost constant value of about 0.4 W as the pump power is larger than 6 W. By comparing P_o and $P_{o,KTP}$ at the pump power of 10 W, we simply estimated the round-trip loss of the resonator to be $L \cong 0.15$ according to the formula: $e^{-L} = P_{o,KTP}/P_o$. Therefore, the linear loss can be calculated as $\gamma = L + \text{Log} [1/R_\omega] = 0.373$. As shown in Fig. 2, the laser firstly turns into irregular QML state at $P_p = 2.0$ W (blue circles) with the large amplitude fluctuation. Then, it reaches the CML state (green triangles) at $P_p = 2.3$ W with the average output power of 173 mW. The highest output power of 2.65W can be obtained from the CML Nd:GdVO₄ laser as the pump power is raised to 10W.

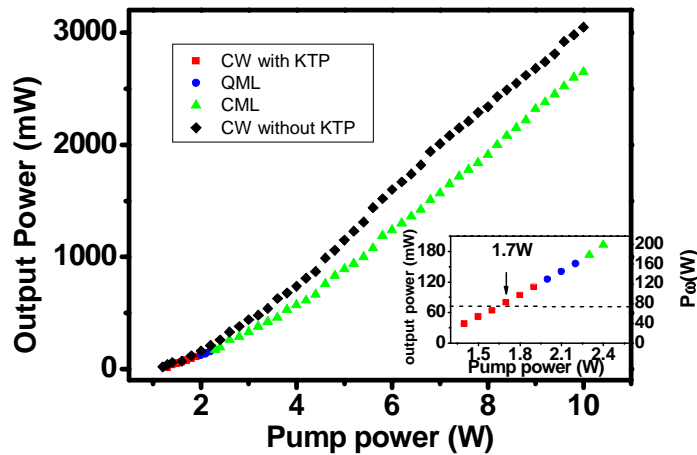


Fig. 2. The average output power versus the pump power with (right) and without (left) the KTP insertion. The inset shows the output power (left axis) and the calculated intracavity peak power P_ω (right axis) for the laser with the KTP at the low pump power.

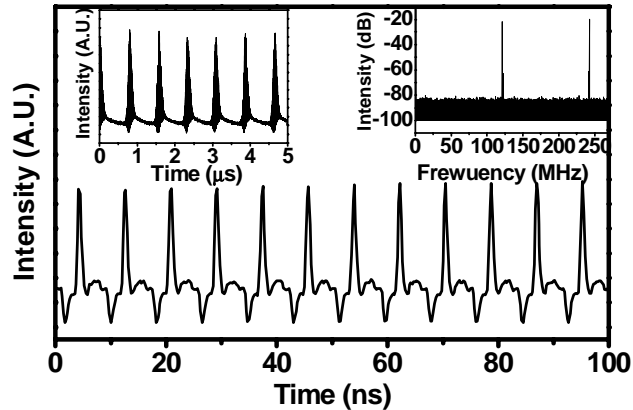


Fig. 3. CML pulse trains on nanosecond-scale with the repetition rate of 121 MHz. The insets show QML pulse trains (left inset) and the RF spectrum (right inset).

The regular CML pulses having 8.3 ns pulse-spacing are revealed in Fig.3 which corresponds to the repetition rate of 121 MHz (right inset of Fig. 3). If we slightly rotate the KTP, the regular QML can be seen in the left inset of Fig. 3, with repetition rate of 1.6 MHz and pulsewidth about 0.1 μ s. The pulsewidth decreases as the pump power increases, and the shortest duration is 38 ps (FWHM, assuming a sech^2 pulse), which is shown in the measured autocorrelation trace of Fig. 4. In addition, the corresponding spectrum measured by the optical spectrum analyzer is shown in the inset of Fig. 4 with center wavelength of 1062.8 nm and FWHM of the bandwidth about 0.1 nm. In our laser, the pulsewidth is longer than that of passively mode-locked Nd doped lasers using other technique such as SESAM. It is due to the group velocity mismatch (GVM) between FW and SHW in the type-II KTP crystal that reduces the available gain bandwidth and prevents back-conversion when the pulsewidth are too short. By using shorter nonlinear crystal, one might reduce the GVM to generate sub-picosecond pulsewidth. Recently, the GVM compensation was reported by using the cascaded kerr lensing with the periodically poled KTP to generate 2.8 ps pulses with 0.6 nm bandwidth [17].

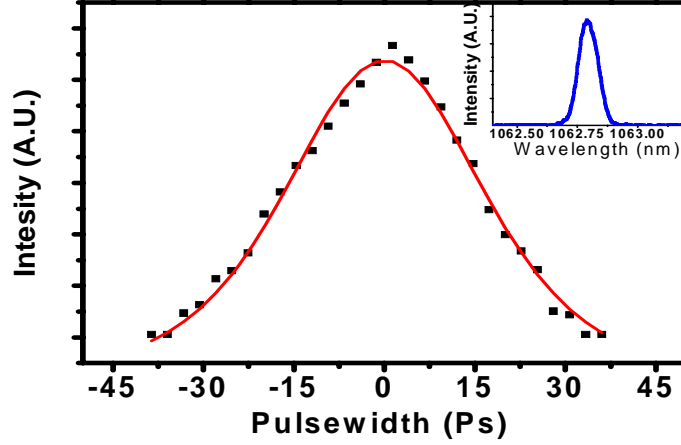


Fig. 4. Autocorrelation curve (sech² fit) of the pulse duration and the corresponding optical spectrum (inset) showing the center wavelength

The threshold pump power of 2.3W for our stable CML in Nd:GdVO₄ laser is much lower than those of NLM-ML Nd:YVO₄ lasers with 15 mm LBO ($P_p = 9$ W, Ref. 12) and 3 mm KTP ($P_p = 10$ W, Ref.13), respectively. It is also much lower than that of $P_p = 13.6$ W for CML Nd:GdVO₄ laser with semiconductor saturable absorber mirror [5]. The threshold for the CML against the QML can be reached as the intra-cavity peak power P_ω exceeds the critical value (P_c) according to [16]:

$$P_\omega \geq P_c = (P_L P_A \Delta R_{max})^{1/2}, \quad (1)$$

where P_L and P_A are saturation powers of the gain medium and the NLM “absorber”, respectively, and $\Delta R_{max} = 1 - R_\omega = 20\%$ is the maximum nonlinear modulation if the nonsaturable loss is nearly zero at high P_ω . We estimated the saturation power of the gain

medium $P_L = I_s(\pi W_g^2)$ to be 3.8 W, since the saturation intensity $I_{sat} = \frac{h\omega_0}{\sigma_L T_L}$, where h is the

Planck constant, ω_0 is the center frequency of the fundamental wave, $\sigma_L = 7.6 \times 10^{-19}$ cm² is the stimulated emission cross section, and $T_L = 90$ μ sec is the fluorescence life time. The saturation power P_A of the NLM [12] is defined as the ratio of the linear loss γ to the first-order nonlinear loss modulation κ introduced by NLM absorber [8], which is:

$$\kappa = -(dL_{nl}/dP_\omega)_{P_\omega=0} = -(\rho/P_\omega) R_\omega [R_\omega + 1 + 2\cos(\Delta k l - \Delta\phi)], \quad (2)$$

where L_{nl} is the round trip loss including the NLM, $\Delta\phi = \phi_{SH} - \phi_{FW}$ is phase mismatch due to the dispersion of the air and the mirror, and $\Delta k = k_{SH} - 2k_{FW}$ is the wave vector mismatch between the FW and SH in nonlinear crystal. In the low conversion efficiency limit, the conversion efficiency ρ from the FW to the SH can be presented as [18]

$$\rho(P_\omega) = \frac{P_{2\omega}}{P_\omega} = l^2 (2\eta^3 \alpha_0^2 d_{eff}^2) \left(\frac{P_\omega}{A}\right) \frac{\sin^2(\Delta k l / 2)}{(\Delta k l / 2)^2}, \quad (3)$$

where $P_{2\omega}$ is the intra-cavity peak power of the SHW, $A = 1.5 \times 10^{-8}$ m² is the area of FW at the KTP, $l = 1$ cm is the length of the KTP, η is the plane-wave impedance, and $d_{eff} = 3.18$ pm/V is the effective second-order nonlinear coefficient. The saturation power $P_A = \gamma / \kappa_{max} = 6.9$ kW is estimated by considering maximal nonlinear loss $\kappa_{max} = (\rho/P_\omega) R_\omega (1 - R_\omega)$ with conditions $\Delta k = 0$ and $\Delta\phi = \pi$. Thus, the critical peak power (P_c) of NLM-ML for CML against QML is estimated from Eq.1 to be about 72 W by assuming pulsewidth of 40 ps, which is shown in the dash line of the inset of the Fig.2. Experimentally, P_ω (estimated from the laser output with

the KTP) is over the P_c for the $P_p=1.7$ W, which is smaller than the practical CML threshold of $P_p = 2.3$ W due to the overestimation of P_ω at lower pumping by assuming the shorter pulsewidth of 40 ps.

4. Conclusion

The nonlinear mirror mode locking of the end-pumped Nd:GdVO₄ laser has been first time to our knowledge demonstrated by using a 1-cm long KTP crystal. Stable CML can be obtained as the pump power increased above 2.3W, which is much lower than those of NLM-ML Nd:YVO₄ lasers. The highest output power of 2.65W at 10 W pump-powers can be reached for stable CW mode-locking with 121-MHz repetition rate. Recently, the multiple pulse splitting and third and fourth harmonic mode locking of the CML pulses have been observed in this Nd:GdVO₄ lasers with the NLM-ML technique. The results will appear in a forthcoming paper. It confirm the excellent laser performances of Nd:GdVO₄ crystal and rich dynamics of the NLM-ML.

Acknowledgments

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