

Rapid communication

Passively mode-locked Nd:YVO₄ laser with up to 13 GHz repetition rate

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Abstract. We demonstrate passive mode locking of a Nd:vanadate (Nd:YVO₄) laser to repetition rates of up to 13 GHz. With Ti:sapphire pumping, we achieved mode locking at 13 GHz with 310 mW of average output power and pulse widths of 9.5 ps. With diode pumping, we achieved mode locking at a repetition rate of 12.6 GHz with 198 mW of average output power and a pulse duration of 8.3 ps.

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Lasers with multi-gigahertz repetition rates are required for applications in the fields of microwave/millimeter-wave communication, photonic switching, telecommunication and particle accelerators. Pulse energies of at least a few picojoules are often required [1]. So far, repetition rates of hundreds of GHz have been achieved with harmonically mode-locked fiber lasers [2], but with typical pulse energies of much less than 1 pJ and often poor stability. Repetition rates even greater than 1 THz have been demonstrated with semiconductor lasers [3], but their pulse energies are far below 1 pJ. Higher pulse energies and average powers in a diffraction-limited beam can be obtained from diode-pumped solid-state lasers. Actively mode-locked solid-state lasers have been demonstrated with 40 GHz repetition rates [4] and 0.5 pJ pulse energies. Passive harmonic mode locking of Cr⁴⁺:YAG lasers has resulted in up to 2.7 GHz with 30.4 pJ pulse energy [5], and with fundamental (i.e. not harmonic) mode locking of solid-state lasers the maximum repetition rate was about 1 GHz with 200 pJ [6]. Another way of generating high-repetition-rate optical pulse trains is to multiply the repetition frequency by using an extracavity dispersive medium [7, 8] or by intracavity spectral filtering [9]. But these techniques add additional complexity and losses to the setup, and they tend to increase intensity fluctuations and pulse duration.

In this work we present very compact diode-pumped Nd:YVO₄ lasers which are stable, self-starting and passively mode-locked at repetition rates of more than 10 GHz with up to 300 mW and more of average output power. A semiconductor saturable absorber mirror (SESAM) [10, 11] was

used as a compact, simple and robust device for passive mode locking. In all cases we operated the laser at its fundamental cavity repetition rate, i.e. the repetition rate of the laser equals the laser cavity free spectral range ($f_{\text{rep}} = c/2nL$) which we will refer to as fundamental mode locking, as opposed to harmonic mode locking, where the repetition rate is an integer multiple N of the cavity free spectral range ($f_{\text{rep, harm}} = Nc/2nL$, $N \geq 2$). As the repetition rate increases, the fundamental mode-locked laser cavity becomes very short, e.g. a 10-GHz laser has a free-space cavity length of only 1.48 cm.

The main challenge of passive mode locking at high repetition rates is to exceed the threshold for Q-switched mode locking (QML) [12]. In this regime, the pulse train is modulated with a Q-switched envelope. As derived in [12], stable cw mode locking (rather than QML) of picosecond lasers is achieved when the intracavity pulse energy E_p exceeds a critical value:

$$E_p > E_{p,\text{crit}} = \sqrt{E_{L,\text{sat}} E_{A,\text{sat}} \Delta R}, \quad (1)$$

where $E_{L,\text{sat}}$ and $E_{A,\text{sat}}$ are the saturation energies of the gain medium and the saturable absorber, and ΔR is the modulation depth of the absorber. Here it is assumed that the laser is operated far above threshold, the absorber is fully saturated, and the absorber fully recovers between two pulses.

By dividing the square of (1) by E_p we obtain

$$E_p > E_{L,\text{sat}} \frac{\Delta R}{S}, \quad (2)$$

where we introduced the saturation parameter $S := E_p/E_{A,\text{sat}}$. For the intracavity laser intensity I_L in the gain medium we obtain the condition

$$I_L > I_{L,\text{crit}} = f_{\text{rep}} F_{L,\text{sat}} \frac{\Delta F}{S} \quad (3)$$

for stable cw mode locking. In order to meet this condition with a high value of f_{rep} , we minimize the other factors on the right-hand side of (3). First of all, a laser medium with small saturation fluence, $F_{L,\text{sat}} = h\nu_L/m\sigma_L$ (with e.g. $m = 2$ for the double pass in a standing-wave cavity), should be chosen. The modulation depth ΔR should be only as large as

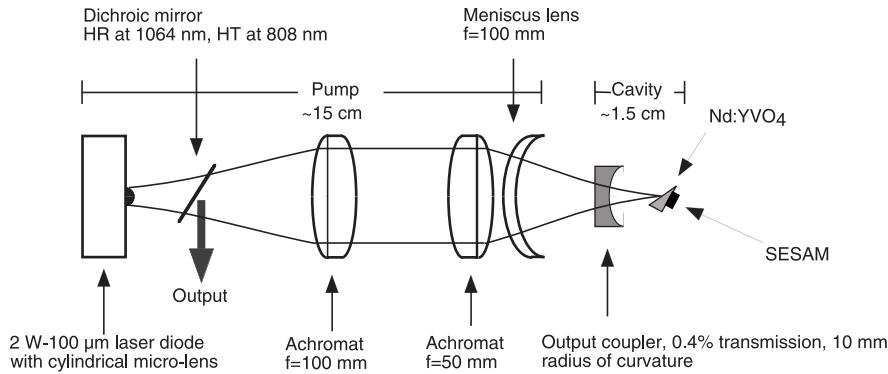


Fig. 1. Setup of diode-pumped Nd:YVO₄ laser with 12.61-GHz repetition rate

necessary for starting and stabilizing the mode-locking process. Furthermore, the saturation parameter S , indicating how strongly the SESAM is saturated, should be made large by keeping the spot size on the SESAM small and/or by choosing a SESAM with small saturation fluence. The value of S is ultimately limited by damage of the SESAM. Finally, I_L can be made large by choosing a small mode size in the laser medium and keeping the cavity losses (including output coupler transmission) as small as possible.

Figure 1 shows the setup of our diode-pumped laser, using a 2-W laser diode from Polaroid with a stripe size of 100 μm and a directly attached cylindrical microlens. The pump optics created a spot at the laser crystal (measured in air) with radii of 15 μm and 25 μm in the sagittal and tangential directions, respectively. The experiments were also carried out with a Ti:sapphire laser instead of the laser diode; in this case a smaller circular spot with 13 μm beam radius (measured in air) was generated. A dichroic mirror was used to extract the laser output beam. The laser medium is a flat/Brewster-cut Nd:YVO₄ crystal with 3% neodymium doping. This material has a low saturation fluence (37.3 mJ/cm^2 , e.g. about 6 times smaller than that for Nd:YAG) and a very short absorption length of 90 μm , so most of the pump power is absorbed within the range where the pump beam is smaller than the laser mode size. The path length in the crystal is about 1.3 mm. The output coupler, placed at about 9 mm from the crystal, has a radius of curvature of 10 mm, a coating with only 0.4% transmission at the laser wavelength and a high transmission ($> 95\%$) for the pump beam at 808 nm. The laser spot on the SESAM has calculated beam radii of 26 μm and 66 μm in the sagittal and tangential directions, respectively, and is only slightly larger (27 $\mu\text{m}/66 \mu\text{m}$) in the gain medium.

The MOCVD-grown SESAM was mounted in direct contact with the laser crystal. It consists of one 15-nm-thick GaAs/In_{0.25}Ga_{0.75}As quantum well embedded in 70 nm GaAs and AlAs spacer layers, a dielectric top mirror with 55% reflectivity for the lasing wavelength of 1064 nm and a GaAs/AlAs bottom Bragg mirror. The measured parameters of this SESAM are $F_{A, \text{sat}} \approx 60 \mu\text{J}/\text{cm}^2$ and $\Delta R\% \approx 0.4\%$, and the recovery time is ≈ 100 ps. The estimated nonsaturable losses are $\approx 0.1\%$.

We have built several Nd:YVO₄ lasers with the same type of cavity and repetition rates of 2.7 GHz, 6 GHz, 9.4 GHz and about 13 GHz. In this paper we describe only the laser with 13 GHz. First we report the experimental results with Ti:sapphire pumping. The threshold pump power (incident on

the crystal) and slope efficiency were 3 mW and 25%, respectively, for pump powers below 1 W. For higher pump powers (up to 1.5 W), the slope efficiency was somewhat lower (Fig. 2). Stable self-starting cw mode locking at a 12.98-GHz repetition rate was achieved for pump powers (incident on the crystal) above 750 mW at an average output power of 189 mW. This is in reasonable agreement with the theoretical expectations. A precise estimate is difficult to obtain; the path length in the crystal and thus the spot sizes are difficult to determine (because of the angled interface), and the SESAM was not fully recovered after one round-trip time. We note that the SESAM was not strongly saturated; the saturation parameter S was only ≈ 2 at maximum power.

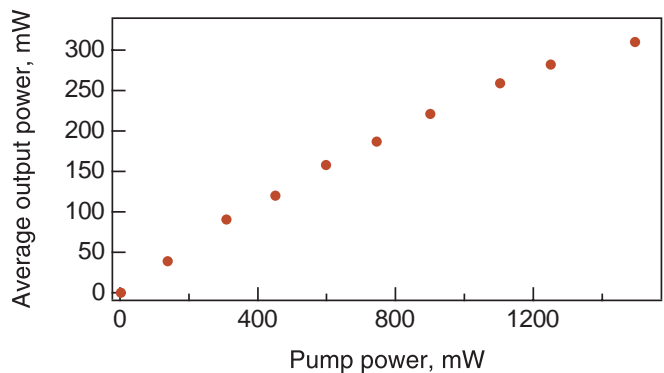


Fig. 2. Pump power versus average output power for the Ti:sapphire-pumped Nd:YVO₄ laser

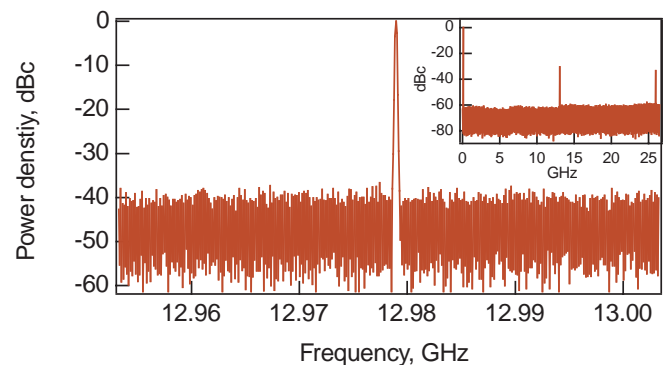


Fig. 3. RF spectrum of Ti:sapphire-pumped laser with 12.98-GHz repetition rate at 1 W of pump power. The inset shows the RF spectrum with a 26-GHz frequency span

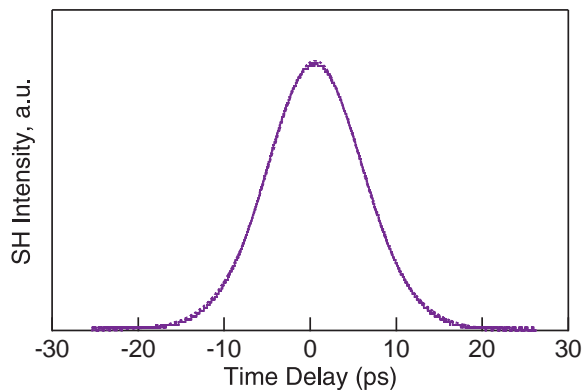


Fig. 4. Measured autocorrelation (dotted) of 8.3-ps pulses from the 12.61-GHz diode-pumped laser at 190 mW. Solid line: sech^2 fit

The RF spectrum (Fig. 3) shows the first harmonic at 12.98 GHz and the second harmonic at ≈ 26 GHz. The maximum output power was 310 mW (corresponding to 77.5 W intracavity power and 24 pJ output pulse energy) at an incident pump power of 1.5 W on the crystal. The pulse duration, measured near the QML threshold with an autocorrelator is 9.5 ps, assuming a sech^2 pulse profile.

With the diode-pumped setup, the air space between the crystal and output coupler had to be increased by a small amount to establish cw mode locking; this leads to somewhat reduced spot sizes on the crystal and on the SESAM ($23 \mu\text{m}/62 \mu\text{m}$), and the repetition rate was 12.61 GHz. The threshold power (3 mW), slope efficiency (22%) and pulse duration (8.3 ps) remained nearly unchanged. An autocorrelation trace is shown in Fig. 4. Stable cw mode locking was achieved with pump powers between 848 mW and 916 mW, corresponding to output powers between 178 mW and 198 mW (14.1–15.7 pJ pulse energy). Figure 5 shows the RF spectrum with the first and second harmonic. For output powers above 198 mW, QML was observed; the reason for this is the excitation of higher-order transverse modes, caused by the poorer beam quality of the pump diode as compared to that of the Ti:sapphire laser.

We have demonstrated passive fundamental mode locking of Nd:YVO₄ lasers with repetition rates as high as 13 GHz and a maximum output power of about 300 mW. The tendency for Q-switched mode locking was suppressed by care-

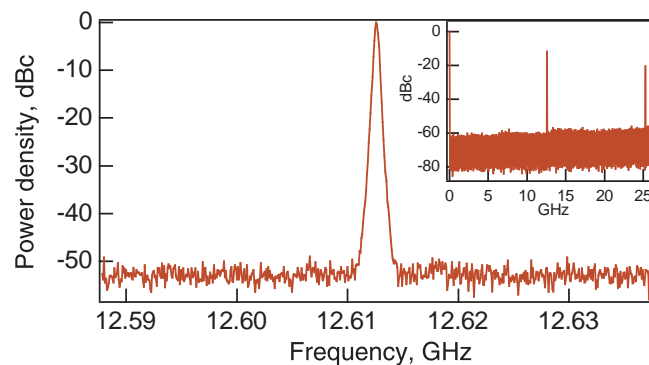


Fig. 5. Averaged RF spectrum of diode-pumped laser with 12.61-GHz repetition rate. The inset shows the RF spectrum with a 26-GHz frequency span

ful optimization of the laser cavity, the gain material and the SESAM.

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