

Multi-GHz tunable-repetition-rate mode-locked Nd:GdVO₄ laser

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Abstract: We report on a simple design for a multi-GHz tunable-repetition-rate diode-pumped picosecond laser. Using a plano-Brewster Nd:GdVO₄ crystal in a V-folded cavity employing only readily available commercial components, we achieved passive mode-locking with 4.4-ps pulses tunable in the range 2.5-2.7 GHz. This laser is meant to be employed in the MIR experiment that aims at the detection of the Schwinger radiation (dynamical Casimir effect).

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OCIS codes: (140.4050) Mode-locked lasers; (140.3480) Lasers, diode-pumped; (140.3410) Laser resonators

References and links

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1. Introduction

High-repetition-rate ultrafast solid-state lasers are interesting for many applications such as high-speed electro-optic sampling, optical clocking and telecommunications. The main feature of the MIR experiment [1] which aims at the detection of the Schwinger radiation (dynamical Casimir effect), is the production of an oscillating reflectivity mirror by shining a laser pulse on a semiconductor, thereby causing the transition of electrons from the valence

to the conduction band. This operation should be repeated at microwave gigahertz frequencies. A high-repetition-rate laser is therefore required.

Recently, passively mode-locked diode-pumped Nd:YVO₄ lasers have been extensively investigated for generation of multi-GHz picosecond pulses, and excellent results are reviewed for example in Refs. [2,3]. In particular, repetition rates up to 160 GHz and output power as high as 2.1 W were reported, with pulses as short as 2.7 ps.

The Nd:GdVO₄ laser crystal was also investigated as a promising candidate for high-repetition-rate sources [4], owing to its superior thermal conductivity that allows for power upscaling, while the absorption peak is broader than that of Nd:YVO₄ and is especially attractive for diode-pumping.

It is well known that stable continuous-wave (cw) mode-locking with semiconductor saturable absorber mirrors (SAMs) requires that the intracavity pulse energy exceed a threshold given by [5]:

$$E_c = \sqrt{F_a F_g A_a A_g \Delta R} \quad (1)$$

where F and A are the saturation fluence and the mode area (the subscripts a, g refer to the absorber and the gain medium, respectively), and ΔR is the modulation depth of the SAM.

Top repetition rates performances achieved to date make use of elegant design solutions [2-4], based on the extensive application of non-standard, expensive, and in any case not easily available optical components, such as SAMs with modulation depth ΔR as low as 0.3%, dichroic pump mirrors with partial reflectivity of $\approx 0.2\%$ - 0.4% at the laser wavelength, and laser diodes with high brightness for optimum mode-matching, resulting in extremely compact and attractive setups.

Still, many applications requiring pulse frequencies in the range of few GHz up to 10-20 GHz do not need resonator designs based on those specialized components and quasi-monolithic devices. The limitations for their supply can be circumvented with a clever simple design relying exclusively on available and inexpensive commercial components.

Based on this design, we built a Nd:GdVO₄ laser generating a stable cw mode-locking train of 4.4-ps pulses at 2.5-2.7 GHz, pumped by a 1-W laser diode emitting at 808 nm. We expect that the repetition frequency can be increased up to ≈ 15 GHz with a straightforward modification of the optical layout, while standard amplification techniques can be implemented whenever higher powers are required.

2. Experiments and discussion

Equation (1) suggests straightforward criteria for achieving cw mode-locking: 1) tightly focus the resonant mode both in the laser crystal and on the SAM device; 2) use small ΔR ; 3) use a low-loss oscillator with high intracavity power (and pulse energy).

Given a standard neodymium doping level of 1%-2% yielding a sufficiently high absorption coefficient α_p at the pump wavelength λ_p , the brightness of commercial broad-area laser diodes (related to their slow-axis beam-quality parameter M_p^2) generally limits the pump waist radius to $W_p \approx \sqrt{\lambda_p M_p^2 / (\pi n \alpha_p)} \approx 30\text{-}40 \mu\text{m}$ [6] (n being the crystal refractive index). This introduces a lower limit for the resonant mode diameter. We also note that the most effective resonator design should minimize the beam waist radius both in the laser crystal and on the SAM device.

The smallest modulation depth ΔR offered with commercial devices is generally around 1% and cannot be reasonably reduced to a small fraction of such a value without accepting large variations in production runs and significantly increased costs.

An ideal low-loss resonator for such an application should employ only high-reflectivity (HR) mirrors and no anti-reflection (AR) optics, since these kind of coatings always brings in

a non-vanishing Fresnel loss of 0.1%-0.2% per pass, of the order of the output coupling that is generally tolerated, which is also comparable to the non-saturable losses of the SAM [1-3].

These considerations led us to propose the design for the high-frequency passively mode-locked oscillator shown in Fig. 1. The pump was a readily available 1-W, 100- μm single emitter diode laser tuned at 808 nm, beam-shaped for end-pumping with aspheric lenses and an anamorphic prism pair. The pump spot radius was measured to be 36 μm . The 3-mm long 1%-doped *a*-cut Nd:GdVO₄ crystal was coated on one side AR at 808 nm and HR at 1063 nm, whereas the second face was cut with a slight offset δ with respect to the Brewster angle. A HR concave mirror, with 25-mm radius of curvature, folded the nearly-symmetric resonator. The folding angle was kept as small as possible, $\approx 6^\circ$, in order to allow maximum overlap of the tangential and sagittal stability regions. The SAM (supplied by BATOP GmbH, Weimar, Germany) was the second end-mirror: the saturable modulation depth was specified to be $\Delta R=0.7\%$ (non-saturable loss $<0.3\%$), with saturation fluence of 30 $\mu\text{J}/\text{cm}^2$ and recovery time <10 ps.

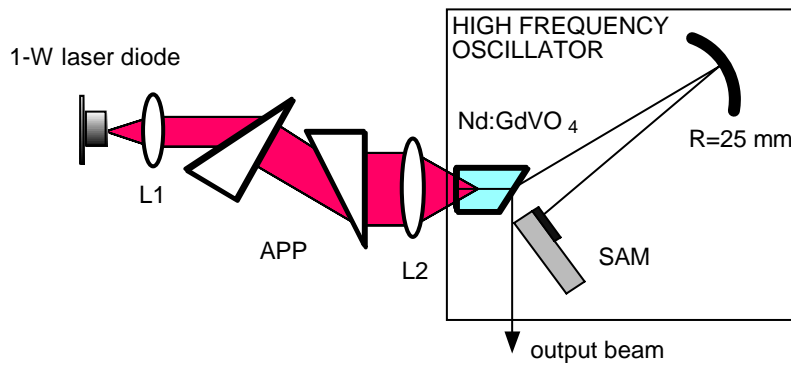


Fig. 1. Layout of the diode-pumped 2.6-GHz Nd:GdVO₄ laser. L1 and L2 are aspheric lenses for collimation and focussing, respectively, and APP is the prism pair for slow-axis expansion.

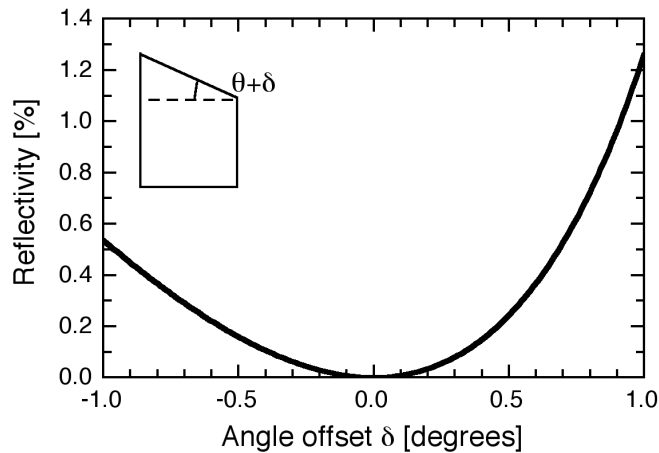


Fig. 2. Fresnel loss from the quasi-Brewster interface as a function of the angle offset. The inclination of the uncoated face yielding exact Brewster incidence is $\theta=24.52^\circ$.

To determine the amount of the loss from the Nd:GdVO₄ quasi-Brewster face, a simpler two-mirror plano-concave cavity was separately set up with a 25-mm radius of curvature,

2%-transmissivity output coupler. The laser emitted up to 250 mW in TEM₀₀ mode with 700 mW of maximum incident pump power, whereas the external reflection from the Brewster face was measured to be $\approx 0.2\%$ of the intracavity power.

Since the working tolerance for crystal cutting is often within 0.5° and the reflectivity dependence from the offset angle δ is parabolic near the Brewster condition, it is easy to specify some offset angle in order to introduce a suitable amount of output coupling (see Fig. 2; see the inset for angle definitions). The shortcoming of this approach is the loss for the internal reflection, and correspondingly reduced laser efficiency, but this is of little concern as long as few tens of milliwatts can be considered a sufficient output power, as in our case.

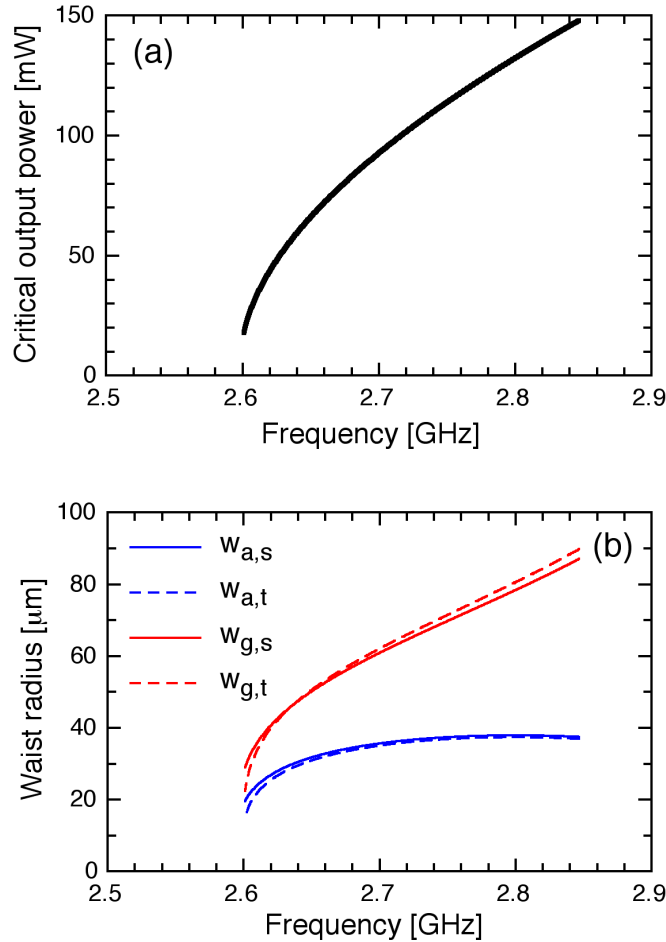


Fig. 3. Numerically computed critical output power for cw mode-locking (a) and waist radii (b) as a function of the repetition frequency. The waist radii on the SAM (w_a) as well as on the gain medium (w_g) are calculated (both for the tangential (t) and the sagittal (s) planes), near the 2.6-GHz edge of the stability region. Actually, the tangential waist radius within the laser crystal has to be multiplied by the refractive index $n=2.192$.

Numerical computation results, summarized in Fig. 3, show the variation of the resonant mode size and of the critical output power [critical energy from Eq. (1) multiplied by the repetition rate frequency], considering the 0.2% effective coupling through the quasi-Brewster face, as a function of the repetition rate.

The output power from the quasi-Brewster face was up to ≈ 60 mW and the repetition rate was centered at 2.6 GHz with pulse duration of 4.4 ps (Fig. 4). The time-bandwidth

product was 0.47, slightly above the $sech^2$ limit as often occurs in lasers with the gain element at the cavity end [7]. The output beam was TEM₀₀ with horizontal polarization. The repetition rate could be varied only slightly (few MHz) by translating the SAM longitudinally without compromising the stability of cw mode-locking. Therefore, in agreement with the numerical modelling, cw mode-locking could be readily achieved only near the edge of the stability region. Once the cw mode-locking was started, the laser could be routinely used without any damage of the SAM.

A radio-frequency spectrum analyzer (HP 8562A) was used to monitor the quality of the mode-locking and to carefully measure the repetition frequency. Owing to the limited photodetector sensitivity, the maximum signal-to-noise ratio was ≈ 30 dB, with no trace of relaxation oscillations in the background noise (the signal on a 500-MHz oscilloscope did not show any low frequency significant envelope modulation).

The flexibility of this cavity design can be appreciated when a broader repetition rate tuning range is required. In fact, a significantly broader tuning range, of ≈ 200 MHz, has been achieved by unbalancing the resonator arms, varying the length of the SAM arm within 30%-50% of the total intracavity path in air, which physically corresponds to right-left shifting the graph in Fig. 3(a). Such a tuning range is important, for example, for matching the pulse frequency to the resonance of a given microwave test device, and cannot be done with linear plano-concave resonators without compromising the cw mode-locking stability.

Reducing the pump power, we found that the critical output power for cw mode-locking was ≈ 30 mW, corresponding to 470 mW of pump power (for comparison, the pump threshold for laser emission with the SAM was ≈ 80 mW). The intracavity critical energy is comparable with that reported in Ref. [4] and is in fair agreement with the prediction of Eq. (1) [see Fig. 3(a)]. It is worth noting that the pulse duration of 4.4 ps is significantly shorter than the 12-ps value previously obtained [4], which may be explained by the larger modulation depth of the SAM used in the present experiment.

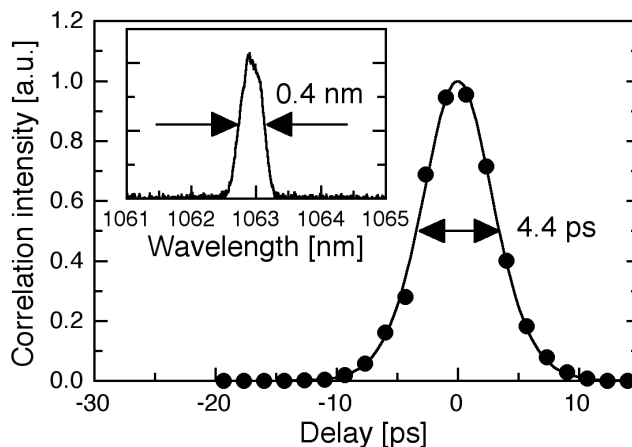


Fig. 4. Non-collinear background-free second-harmonic autocorrelation and spectrum of the passively mode-locked laser (inset).

Exploiting the same criteria to model more compact resonators, devices with pulse frequency up to ≈ 15 GHz can be built. To this end, a stronger pump absorption is desirable, usually corresponding to 2% doping level of neodymium-doped vanadate crystals. Using in this case Nd:YVO₄ instead of Nd:GdVO₄ would allow twice a lower saturation fluence and easier fulfillment of Eq. (1) for a more successful operation.

3. Conclusions

A 2.6-GHz, 4.4-ps passively mode-locked Nd:GdVO₄ laser has been reported. The proposed cavity design helps to minimize the critical energy for cw mode-locking as well as the intracavity losses, allowing the laser to operate with modest pump power levels. The additional degree of freedom introduced by the three-mirror resonator design also allows for a relatively wide 200-MHz tuning of the repetition rate, simply by changing the ratio between the lengths of the two resonator arms. From numerical modelling, we also expect to scale the pulse frequency up to ≈ 15 GHz, especially considering the use of Nd:YVO₄, which is a more suitable material for low-power high-frequency lasers. It should be clear that the laser described in this work was not optimized for high-power operation; however simple amplification schemes [8] can be devised to rise the output power to the Watt level for some especially demanding applications.

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