PHOTONICS Research

High power, microjoule-level diffraction-limited picosecond oscillator based on Nd:GdVO$_4$ bulk crystal

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1.2 μJ pulses with average power of 9 W were directly generated from a passively mode-locked picosecond oscillator based on a Nd:GdVO$_4$ bulk crystal. Short cavity operation in continuous wave and mode-locking regimes was conducted first to confirm the resonator performance and proper alignment. With a carefully calibrated *q*-preserving multi-pass cell inserted into the laser cavity, the cavity length of the original short cavity was extended while the mode-matching condition was maintained fairly well. Compared with the short cavity, nearly fivefold energy enhancement was achieved while the diffraction-limited beam quality was undisturbed. To the best of our knowledge, this is the highest output power ever produced from a mode-locked oscillator based on a single bulk crystal at a repetition rate below 10 MHz without cavity dumping.

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1. INTRODUCTION

Solid-state oscillators with repetition rates on the order of several megahertz possess numerous advantages over general oscillators with 50–100 MHz repetition rates [1–3]. Additional pulse pickers or intracavity modulators can be applied to reduce repetition rate for the latter, but they add complexity and cost. Without resorting to any high-speed or high-voltage elements, insertion of a multi-pass cell (MPC) offers yet a straightforward, cost-effective alternative to increase cavity length and thus reduce repetition rate [4–7]. It also provides a simple method to scale up pulse energy, hence suppressing *Q*-switching instabilities and enhancing Kerr nonlinearity for low-average-power laser systems [8–11]. If high average power is obtained at the same time, pulse energy at the microjoule level can be achieved, resulting in much higher peak power, which is also beneficial for applications in nonlinear optics [12–15]. This type of MPC has already been successfully implemented in mode-locked thin-disk lasers. Sparing the complexity of further amplification, a pulse energy as high as 80 μJ was generated at a repetition rate of 3.03 MHz in a vacuum environment [16]. Picosecond oscillators with enhanced pulse energy up to the microjoule level can be directly used for some industrial micromachining and dental ablation investigations [17–19]. They can also serve as energetic seeds to simplify amplifier systems such as eliminating bifurcation phenomena in high-repetition-rate regenerative amplifiers [20], as well as facilitate direct energy extraction in multi-pass amplifiers [21].

With excellent optical and mechanical properties as well as capacity to conveniently be pumped with laser diodes, neodymium-doped vanadate laser crystals are one of the most ideal series of gain media for compact solid-state picosecond lasers with linearly polarized output. Such sources could be obtained by dual-crystal configurations [22,23], but much more complexity would be added. In practice, an oscillator built with a single crystal is much more preferred as the robust seed of a laser system. In 2003, three modes of repetition rates were realized by a flexible extra-long MPC to produce 4.1 W at 4.1 MHz and 3.5 W at 1.5 MHz with a bulk Nd:YVO$_4$ crystal [12]. By implementing a dual mode-locking technique involving both quadratic polarization switching and a semiconductor saturable absorber mirror (SESAM), 1.5 W output power at 3.95 MHz was produced by a bulk Nd:GdVO$_4$ crystal in 2006 [24]. To seed a regenerative amplifier, an oscillator based on a bulk Nd:LuVO$_4$ crystal with 7 W maximum output power at 11.5 MHz was produced in 2016 [20]. Nd:GdVO$_4$ is an attractive applicant for high-power lasers because of its considerably higher thermal conductivity, which makes it an ideal combination by merits of Nd:YVO$_4$ and Nd:YAG [25].

In this work, we demonstrate a high-power microjoule-level passively mode-locked picosecond oscillator with a single end-pumped Nd:GdVO$_4$ crystal combined with a SESAM and a *q*-preserving MPC. Based on the designing principles for large-volume fundamental mode resonators [26], a mode-matching

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short cavity was designed with high alignment stability. When an MPC was inserted into the laser cavity, the output pulse energy increased to 1.17 μJ, with a pulse width of 26 ps at a repetition rate of 7.7 MHz, amounting to an output average power of 9 W. As a result of careful configuration of the original short resonator and appropriate calibration of compensating optics to restore the *q*-preserving feature of the multi-pass cavity, the beam quality factors in both orthogonal directions were better than 1.05. This is, to the best of our knowledge, the highest output power ever produced from a mode-locked oscillator based on a single bulk crystal at a repetition rate below 10 MHz without cavity dumping. This oscillator has provided trouble-free operation for over a year, indicating its capability to serve as a robust seed source for amplifiers or an economical tool for industrial micro-machining and scientific analysis.

2. EXPERIMENTAL SETUP

The experimental setup of the passively mode-locked picosecond oscillator is illustrated in Fig. 1. The pump source was a fiber-coupled laser diode with a core diameter of 400 μm and numerical aperture of 0.22. The pump wavelength was centered at 879 nm. A pair of achromatic lenses with a magnification of 1:2 was used to collimate and then focus the pump beam into the center of the crystal. An *a*-cut Nd:$GdVO_4$ crystal with 0.5 at. % doping was adopted. The crystal had dimensions of 4 mm (*a*) × 4 mm (*c*) × 8 mm (*a*). Both polished facets of the crystal were antireflection (AR) coated at 879 and 1063 nm. The crystals were wrapped with indium foil and mounted in a water-cooled copper block. The temperature of the cooling water was maintained at 15°C during operation. The maximum incident pump power into the gain medium was 26 W.

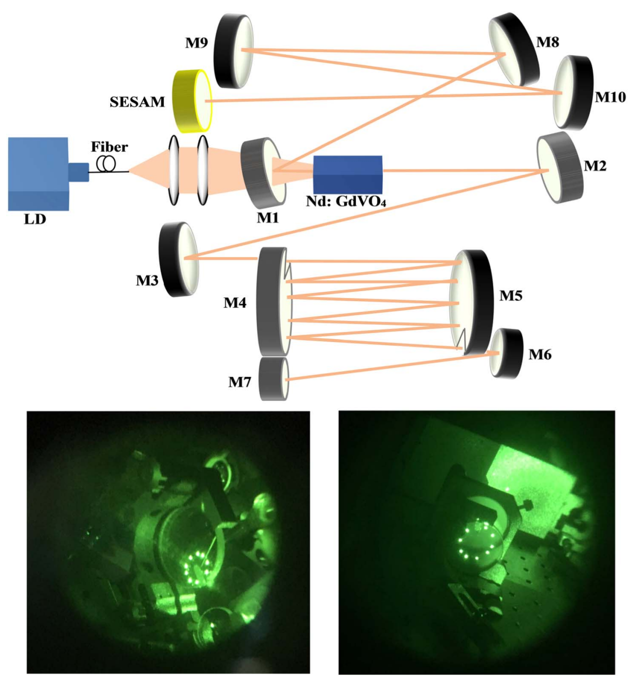

Fig. 1. Schematic of the passively mode-locked picosecond oscillator extended with a *q*-preserving MPC. The insets show spot patterns on the MPC mirrors.

A dichromatic mirror M1 was coated with AR at 879 nm and high reflectivity (HR) at 1063 nm. A SESAM (BATOP GmbH) was used as the passive mode-locking device, which had a modulation depth of 1.8% and relaxation time of 10 ps. The copper heatsink of the SESAM was cooled by cycling water to diminish possible thermal effects. At the preliminary alignment stage, the MPC was not included, and we refer to this cavity without an MPC as a short cavity. With the SESAM shown in Fig. 1 replaced by a plane mirror M11 HR at 1063 nm (not depicted in the figure), the short cavity was terminated by M7 and M11, and M7 was used as an output coupler with a transmission of 30%. CW operation was performed first to confirm the appropriate alignment of the cavity. Three curved mirrors M8 ($R = 1000$ mm), M9 ($R = 1000$ mm), and M10 ($R = 200$ mm) were chosen to obtain the proper beam size on the SESAM for stable continuous-wave mode-locking (CWML) short-cavity operation. When the SESAM was inserted into the cavity, the cavity length for short-cavity CWML operation was 3.34 m. Then the *q*-preserving MPC was inserted to extend the cavity, in which the mode-match condition was undisturbed. We refer to this extended cavity as a long cavity. The MPC was designed to introduce a total of ten round trips per pass, and it consisted of a flat HR mirror M4 and a concave mirror M5 ($R = 1200$ mm). Both M4 and M5 have triangular notches for beam entry and exit, so ten full roundtrips could not be completed, and compensation elements were incorporated to get the MPC *q*-preservation [27]. Consequently, the beam leaving M5 was reflected by a curved mirror M6 ($R = 1200$ mm) right behind M5 and then was sent back by the plane output coupler M7. The periodic length of the MPC was 785 mm, constituting a total cavity length of approximately 19.5 m while keeping a reasonable footprint. The insets in Fig. 1 show spot patterns on the mirrors of the MPC. A different combination of three curved mirrors M8 ($R = 500$ mm), M9 ($R = 1000$ mm), and M10 ($R = 1000$ mm) was applied to accommodate for the expected higher intracavity energy for stable CWML operation while the mode size on the Nd:$GdVO_4$ crystal remained unchanged. The curvatures and distances between mirrors were optimized for best beam quality and highest optical efficiency at full pump power.

3. EXPERIMENTAL RESULTS AND DISCUSSION

In CW operation, a maximum output power of 12 W was obtained at an absorbed pump power of 19.7 W. For short-cavity CWML operation, a maximum CWML laser output power of 11 W was achieved when the absorbed pump power and output coupling remained the same. The repetition rate is 44.9 MHz and the pulse energy is 245 nJ.

A maximum output power of 9 W was attained in long-cavity CWML operation at 1062.9 nm, corresponding to a 46% optical efficiency. Given the amount of reflections on MPC mirrors per roundtrip that increase the optical losses, the output power decreased in comparison with that in the short-cavity operation regime under similar conditions. The output performances of three different operation regimes are shown in Fig. 2. The power scaling in our specific configuration was limited by our pump power supply (26 W provided by a nominal

30 W laser diode). For more general cases, as long as the heat caused by the pump does not distort the beam or fracture the crystal, a configuration like this is power scalable assuming the large-volume fundamental mode resonator can be figured out and proper beam size on the SESAM is arranged.

A steady oscilloscope (Tektronix DPO71254C) trace of the long-cavity pulse train with a repetition rate of 7.7 MHz was detected with a fast photodiode and is depicted in Fig. 3, corresponding to a pulse energy of 1.17 μJ from a single-crystal oscillator. Nearly fivefold energy enhancement was achieved compared with the short-cavity CWML regime. No damage to the saturable absorber was observed throughout the operation, and stable mode-locking behavior was confirmed by the typical radio frequency (RF) spectrum. The RF spectrum signal of the oscillator was monitored at a frequency window of 1 MHz with 1 kHz resolution bandwidth (RBW) and a window of 100 MHz with 100 kHz RBW, as recorded in Fig. 4.

The temporal characteristic of the long-cavity output pulse was confirmed by an intensity autocorrelator (FR-103XL, Femtochrome Research, Inc.). As shown in Fig. 5, the output pulse duration (full width at half-maximum, FWHM) was measured to be 26 ps, assuming the pulse had a Gaussian temporal intensity profile. No enhanced spatial hole burning effect, relatively large output coupler transmission, and a lack of

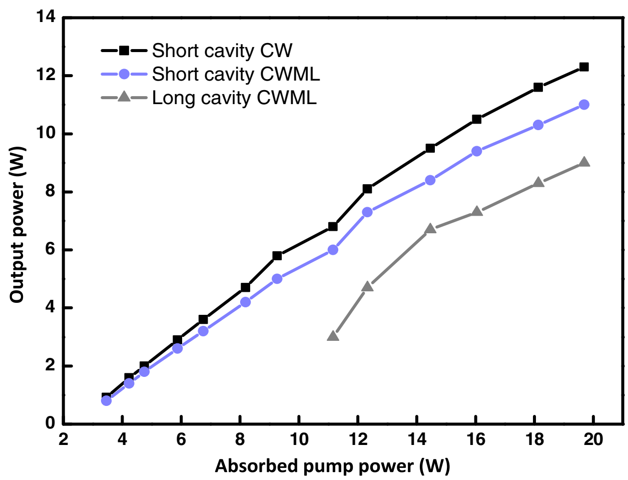

Fig. 2. Output performance of three different operation regimes.

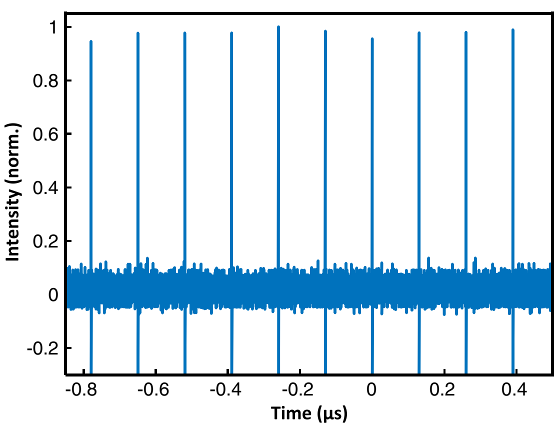

Fig. 3. Oscilloscope trace of the pulse train at a repetition rate of 7.7 MHz.

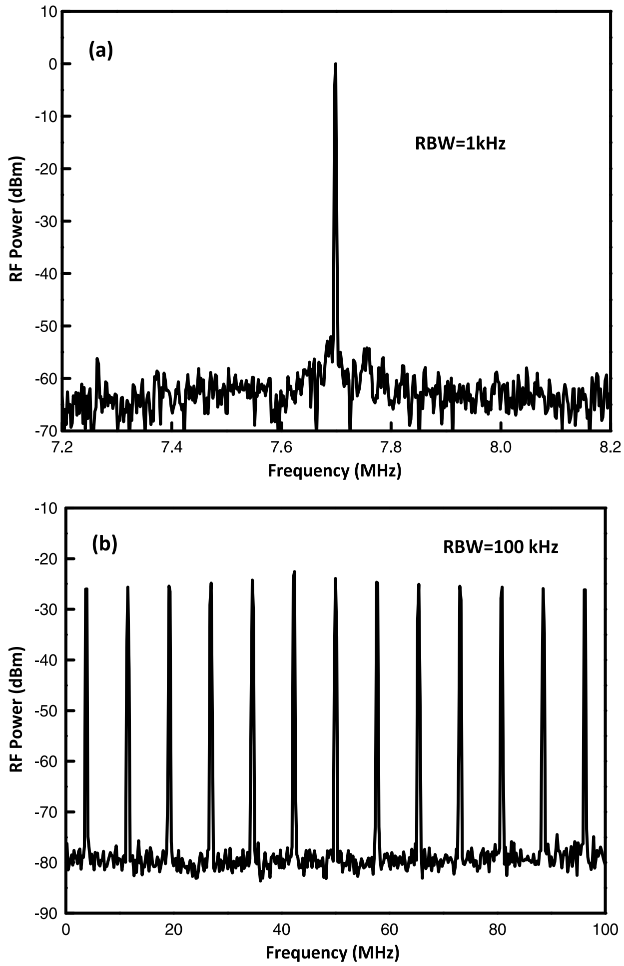

Fig. 4. Radio frequency spectrum of the oscillator (a) at the fundamental beat note with a resolution bandwidth of 1 kHz, and (b) at the 100 MHz wide span range with a resolution bandwidth of 100 kHz.

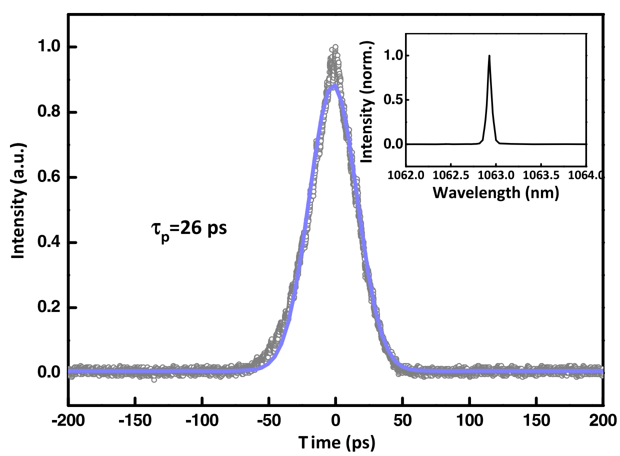

Fig. 5. Measured autocorrelation trace, assuming a Gaussian-shaped pulse; inset shows the optical spectrum of the output pulses.

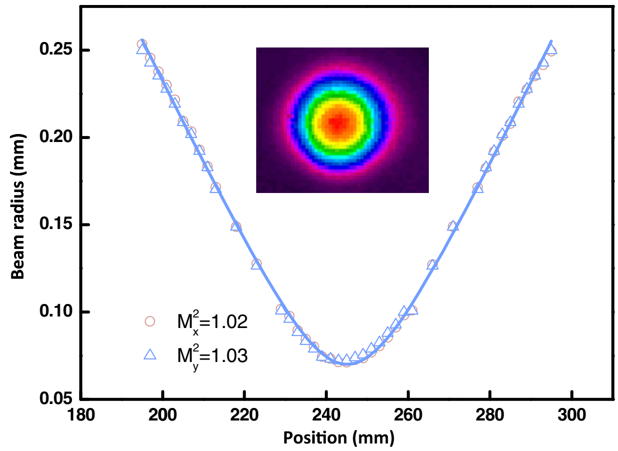

Fig. 6. Beam quality and far-field beam profile.

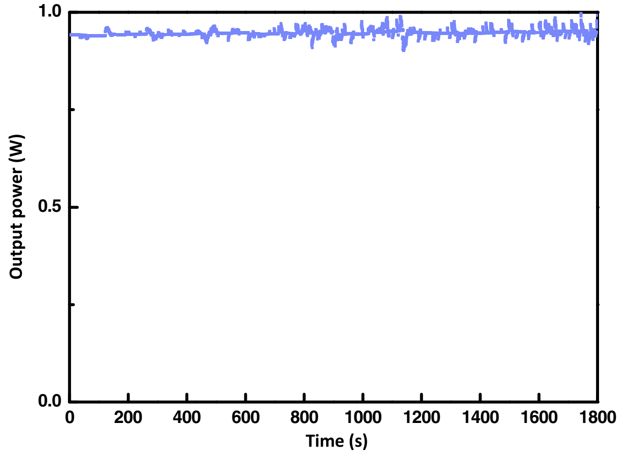

Fig. 7. Power stability of the oscillator output at full pump power.

dispersion compensation elements were three main factors that limited pulse shortening in this setup. Pulse duration could be decreased in future setups.

The detailed spatial profile of the long-cavity output beam was also characterized by a CCD camera (Ophir Spiricon LBA-USB L230), indicating a diffraction beam quality of $M_x^2 = 1.02$ and $M_y^2 = 1.03$ in the orthogonal directions (shown in Fig. 6), with the excellent short-cavity beam quality preserved. The inset in Fig. 6 displays the far-field beam profile at the focus. The well-maintained spatial quality of the short cavity confirms proper configuration and alignment of the q-preserving MPC.

Additionally, the long-term power stability of long-cavity operation was characterized with a power meter at full pump power. A standard deviation of <0.8% was measured in a time interval of 30 min, as depicted in Fig. 7, and the pulse-to-pulse stability in the output was measured to be <1.5%. Better performance is feasible with an improved pump supply and system housing.

4. CONCLUSION

In conclusion, we have demonstrated a high-power diode-pumped SESAM mode-locked $Nd:GdVO_4$ oscillator with output pulse energy of nearly 1.2 μJ. Stable output trains of 26 ps pulses were obtained in a high-quality output beam ($M^2 < 1.05$). The average power was 9 W at a repetition rate of 7.7 MHz. To the best of our knowledge, this is the highest output power ever produced from a mode-locked oscillator based on a single bulk crystal at a repetition rate below 10 MHz, without cavity dumping. Further power scaling is available by adopting a dual-crystal scheme, but this would inevitably add complexity. This high-power oscillator, with microjoule-level pulse energy and diffraction-limited beam quality, could have a significant number of industrial, scientific, and biomedical applications.

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