Optics & Laser Technology 87 (2017) 26–30

Contents lists available at ScienceDirect

Optics & Laser Technology

journal homepage: www.elsevier.com/locate/optlastec

Full length article

# 10 kHz ps 1342 nm laser generation by an electro-optically cavity-dumped mode-locked $Nd:YVO_4$ laser

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ARTICLE INFO

*Article history:*
Received 24 February 2016
Received in revised form
20 June 2016
Accepted 30 July 2016

*Keywords:*
Electro-optically cavity-dumped
Mode-locked
1342 nm laser

ABSTRACT

We have demonstrated an electro-optically cavity-dumped mode-locked (CDML) picosecond $Nd:YVO_4$ laser at 1342 nm with 880 nm diode-laser direct pumping. At a repetition rate of 10 kHz, an average output power of 0.119 W was achieved, corresponding to a pulse energy of 11.9 μJ. Compared with the continuous wave mode-locking pulse energy of 17.5 nJ, the CDML pulse energy was 680 times higher. The pulse width was measured to be 33.4 ps, resulting in the peak power of 356 kW. Meanwhile, the beam quality was nearly diffraction limited with an average beam quality factor $M^2$ of 1.29.


## 1. Introduction

Picosecond (ps) laser systems at 1.3 μm have been applied in many fields such as selective scribing of Copper Indium Gallium Selenide (CIGS) photovoltaics, stealth wafer dicing, and efficient harmonic generation [1]. Short pulse 1.3 μm laser sources with high energy and high peak power are required for highly efficient frequency conversion to the visible and ultraviolet spectral range by high order harmonic generation and other parametric processes. Especially, laser sources around 167 nm in the deep-ultraviolet (DUV) region obtained by eighth harmonic generation of 1.3 μm lasers have higher photon energy than traditional 177.3 nm, which may be used in angle-resolved photoemission spectroscopy and optical atomic clock [2,3]. A common way to obtain ps pulse laser source at 1.3 μm is mode-locked technology in a diode-laser (LD) pumped neodymium doped crystal laser, and $Nd:YVO_4$ is a favorable gain medium due to its large stimulated emission cross ($6 \times 10^{-19}\,cm^2$) at 1342 nm. There are several reports on continuous wave mode-locked (CWML) pulses relying on a sequence of two elementary second-order nonlinear processes or using intracavity semiconductor saturable absorber mirrors (SESAMs) at 1342 nm [4,5]. For example, an average power of 1.52 W nonlinear-mirror mode-locked 1342 nm $Nd:YVO_4$ laser using a periodically poled $LiNbO_3$ crystal and a dichroic mirror at a pulse repetition rate (PRR) of 101 MHz (MHz) with a pulse duration of 9.5 ps has been reported. This leads to a pulse energy of 15 nJ and a peak power of 1.6 kW, respectively [4]. In addition, an average output power of 7.63 W passively mode-locked 1342 nm $Nd:YVO_4$ laser was obtained with a PRR of 77 MHz and a pulse duration of 24.2 ps using a SESAM. Its corresponding pulse energy and peak power were 99 nJ and 4.1 kW, respectively [5]. Most pulse energy obtained directly from the mode-locked lasers was quite low usually at nJ level due to the high repetition rate of MHz order. For amplifying the output power of SESAM mode locking further, our group adopted the master oscillator power amplifier (MOPA) system. With two amplifier modules, a MOPA system produced 16.38 W of output power at 1342 nm with a PRR of 77 MHz and a pulse duration of 20.2 ps, resulting in 0.21 μJ of pulse energy and 10.5 kW of peak power, respectively [6]. However, this system was quite complicated, and the laser source always operated at high repetition rate of around hundred MHz level. In such a time, regenerative amplifier (RGA) is under consideration for obtaining higher pulse energy and higher peak power ps pulse laser at 1.34 μm, which is a preferable approach to boost the pulse energy to the mJ-level. A 1342 nm ps $Nd:YVO_4$ RGA operating from 1 to 10 kHz was obtained with a maximum pulse energy of 0.243 mJ and a maximum peak power of 5.55 MW [7]. Moreover, a RGA produced pulses of ∼13 ps duration at 300 kHz repetition rate with an average output power of 11 W. Attained peak power of

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http://dx.doi.org/10.1016/j.optlastec.2016.07.021
0030-3992/

~2.8 MW facilitated conversion to the 2nd, 3rd, and 6th harmonics at 671 nm, 447 nm, and 224 nm [1]. But, these systems are complicated and costly on account of the two resonators. Meanwhile, one way to reduce the complexity and operate at kHz is the usage of diode-pumped cavity-dumped laser in combination with highly reliable mode-locking technique using a SESAM – cavity-dumped mode-locked (CDML) laser, which is an alternative method to efficiently generate high pulse energy and requires only a single resonator resulted in lower costs, comparable compactness, and insensitivity to misalignment [8]. Liu et al. obtained a cavity dumped 1342 nm Nd:$YVO_4$ laser approach using an electro-optic (EO) device, whose pulse width was 4.7 ns due to a lack of any mode-locked device [9]. However, most ps CDML were operating at 1 μm [10–12], and there have been rarely reports on the ps CDML laser at 1.3 μm to date. Since Nd:$YVO_4$ at 1342 nm has smaller stimulated emission cross and larger quantum defect than that at 1064 nm, so it is comparatively difficult to obtain the CDML at 1342 nm. In order to achieve the stable operation of the 1342 nm CDML laser with high efficiency, both the thermal management issues and optimal resonator design should be taken into consideration simultaneously.

In this letter, we introduced an EO CDML picosecond Nd:$YVO_4$ laser at 1342 nm. In the laser system, a single mode-locked laser pulse is generated and cavity-dumped by using a SESAM and an electro-optic modulator. At a PRR of 10 kHz, an average output power of 0.119 W was achieved under the absorbed pump power of 25.81 W, corresponding to a pulse energy of 11.9 μJ. Meanwhile, the beam quality was nearly diffraction limited with an average beam quality factor $M^2$ of 1.29. The pulse width was measured to be 33.4 ps, resulting in the peak power of 356 kW. To the best of our knowledge, it was the first time reported from picosecond CDML oscillator at 1342 nm.

## 2. Experiments setup

The schematic setup of the device is outlined in Fig. 1. The picosecond Nd:$YVO_4$ laser with EO cavity dumping was an end-pumped system, which was passively mode-locked with a SESAM. In the experiment, a fiber coupled laser diode was employed as the pump source, which had a core diameter of 400 μm, a numerical aperture of 0.22, and the maximum output power of 150 W at 880 nm. The pump beam from the fiber end was focused into the laser crystal with a spot diameter of about 800 μm. The gain medium was an a-cut composite Nd:$YVO_4$ crystal with the dimensions of 3 mm × 3 mm × 21 mm; the middle part of the crystal

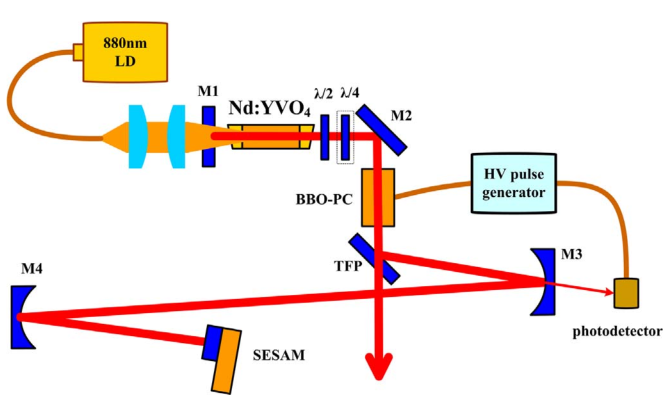


**Fig. 1.** Experimental setup for the LD-end-pumped EO CDML Nd:$YVO_4$ laser. M1-M2:HR at 1342 nm and AR at 1064 nm & 880 nm, M3-M4:HR at 1342 nm and AR at 1064 nm & 880 nm with the radii of curvature of −1000 mm and −500 mm, TFP: thin film polarizer at 1342 nm, λ/2: half-wave plate, λ/4: quarter-wave plate, BBO-PC: BBO Pockels cell, SESAM: semiconductor saturable absorber mirror.

was 15 mm long with 0.5 at% $Nd^{3+}$-doped for its good laser characteristic; two 3 mm undoped $YVO_4$ ends were bonded to both facets of the crystal for reducing the thermal effect. The crystal had a high anti-reflection (AR) coating for 1342 nm, 880 nm and 1064 nm on both end facets, and was double-end-wedged cut at 2° to suppress potential Fabry-Perot etalon effect. The laser crystal was wrapped with indium foil in a water cooled copper block maintained at 20 °C. The CDML cavity was a folded resonator consisted of five mirrors and a SESAM. We employed a reflective SESAM (BATOP GmbH) centered at 1340 nm to achieve mode locking with a saturation fluence of 90 μJ/$cm^2$ and a fast relaxation time of ~1 ps. Its modulation depth and non-saturable loss were 0.6% and 0.4%, respectively. The heat loaded on the SESAM was handled simply by mounting a copper block with the SESAM soldered on a small copper heat sink, which was also cooled by water at temperature of 20 °C. The flat mirrors M1 and M2 were AR coated at 880 nm and 1064 nm, and high-reflection (HR) coated at 1342 nm. Concave mirrors M3 and M4 were coated HR at 1342 nm and AR at 1064 nm with the radii of curvature of −1000 mm and −500 mm, respectively, which were used to compensate the thermal lens effect in the crystal and obtain appropriate laser mode both in the crystal and on the SESAM. The distance between M3 and the right end of the laser crystal was approximately 320 mm; M3 and M4 were separated by 1220 mm; the SESAM was placed 300 mm away from M4; the total cavity length was about 1930 mm. A quarter-wave plate (λ/4) and a BBO Pockels cell (PC) were inserted in the CDML's cavity. Cavity dumping was accomplished with the PC and a thin film polarizer (TFP). We used the extraordinary π-direction of the Nd:$YVO_4$ crystal in the experiment, but the polarization of laser was horizontal. So we inserted a half-wave plate (λ/2) in the cavity for the vertical polarization operation. The value of the quarter-wave voltage for the BBO is given by [13,14]

$$V_{\lambda/4} = \frac{\lambda d}{4n_o^3 r_{22} L}, \tag{1}$$

which depends on the laser wavelength ($\lambda = 1342$ nm), the crystal thickness ($d = 4$ mm), the refractive index of the crystal ($n_o = 1.65$), the effective electro-optic coefficient ($r_{22}$ ~1.87 pm/V) and the crystal length ($L = 25$ mm). The value of the quarter-wave voltage was calculated to be about 6390 V.

## 3. Results and discussions

We firstly studied the high-power continuous wave mode-locking operation, which was performed to confirm the appropriacy of the configuration. The fast axis of the quarter-wave plate was rotated by 5° from the vertical direction, so the quarter-wave plate and the TFP together acted as an output coupler with the quarter-wave voltage off on the BBO. In CWML operation, a maximum output power of 1.36 W at a PRR of 77.6 MHz was obtained under an absorbed pump power of 28 W. The corresponding pulse energy was 17.5 nJ. We employed a <40 ps rise time photodetector (ALPHALAS, UPD-40-UVIR-D) and monitored by a Tektronix oscilloscope with a 1 GHz band width to observe the output pulse. The oscilloscope waveform of the stable mode locked pulse train obtained from a transmission of the TFP was shown in Fig. 2(a) and Fig. 2(b). The oscilloscope trace showed that the laser was mode locked stably with the SESAM at 77.6 MHz and the peak-to-peak amplitude fluctuation was less than ±3.1%.

Secondly, when the quarter-wave plate was rotated at the angle of its fast axis parallel with the vertical direction or was removed, the laser was still under CWML operation due to the unavoided leaking of the optical elements. The output power from the TFP