532-nm picosecond pulse generated in a passively mode-locked $Nd:YVO_4$ laser

Weiwei Wang (王伟卫)[1], Jie Liu (刘 杰)[1*], Fei Chen (陈 飞)[1],
Lei Li (李 雷)[1], and Yonggang Wang (王勇刚)[2]

[1] *College of Physics and Electronics, Shandong Normal University, Ji'nan 250014, China*
[2] *Division of Microelectronics, School of Electronical and Electroinc Engineering,*
Nanyang Technological University, Singapore 639798
[*] *E-mail: jieliu@sdnu.edu.cn*

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A diode-pumped continuous-wave (CW) mode-locked $Nd:YVO_4$/KTP green laser with semiconductor saturable absorber mirror (SESAM) is demonstrated. The maximum output power of CW mode-locked green laser is obtained to be 552 mW at the incident pump power of 7.25 W, corresponding to an optical-optical conversion efficiency of about 7.6%. The 532-nm CW mode-locked pulse duration is estimated to be about 8.4 ps with the repetition rate of 87 MHz.

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Diode-pumped solid-state green lasers with short pulse duration, high pulse energy, and high repetition rate are attractive for a wide range of applications, e.g., high-density optical storage, surgery, angioplasty, and optical testing. Two crystals are very important for those green lasers. One is the $Nd:YVO_4$ crystal, due to its high absorption coefficient, short lifetime of the upper level, and large stimulated emission cross section, and it is very suitable for achieving mode-locked operation[1−3]. The other is the KTP crystal which has high nonlinear conversion coefficient. So it is easy for $Nd:YVO_4$/KTP green lasers to obtain high second harmonic conversion efficiency[4−6].

There are already some reports on diode-pumped mode-locked $Nd:YVO_4$ green lasers[7−10]. In those papers, the mode-locked $Nd:YVO_4$ laser of 532 nm were based on the cascaded second-order nonlinearity mode-locking (CSM) and nonlinear mirror mode-locking (NLM). The CSM and NLM mode-locking mechanisms were similar in using an artificial fast saturable absorber. Recently, the development of mode-locked laser technology has been made with the application of real saturable absorbers. For example, semiconductor saturable absorber mirror (SESAM) has been recognized as a practical way to obtain stable picosecond pulses. Li *et al*. reported a continuous-wave (CW) mode-locked green laser with SESAM, which used $YVO_4/Nd:YVO_4$ as the gain medium[11]. However, as far as we know, the CW mode-locked $Nd:YVO_4$/KTP green laser by employing SESAM as saturable absorber has not been reported.

In this letter, we demonstrate the experiment of a passively CW mode-locked $Nd:YVO_4$/KTP green laser with SESAM as saturable absorber and using an intracavity frequency doubling KTP crystal. The maximum output power of 552 mW at 532 nm with a repetition rate of 87 MHz is obtained at the incident pump power of 7.25 W. The mode-locked pulse duration of green laser is about 8.4 ps, corresponding to the peak power of about 709 W.

The schematic setup of the passively CW mode-locked green laser is depicted in Fig. 1. The pump source used in our experiment was a 30-W fiber-coupled diode laser (LYPE30-SG-WL808-F400) with the output wavelength ranging from 806 to 809.5 nm at 27.5 °C and the numerical aperture of 0.22. The spot size inside the crystal was about 200 μm. The laser crystal was a-cut $Nd:YVO_4$ crystal with the Nd^{3+} concentration of 0.5% and dimension of 4×4×8 (mm). The input mirror with high transmittance (HT) at the pump wavelength of 808 nm and high reflection (HR) at both the fundamental wavelength of 1064 nm and the second-harmonic wavelength of 532 nm was coated on one side of the laser crystal. The other side was coated for HT at both 1064 and 532 nm. The laser crystal was wrapped with indium foil and mounted in a water-cooled copper block; the water temperature was maintained at 18 °C. This active cooling ensures stable output power and avoids the thermal fracture of the host crystal. The KTP crystal utilized as a frequency doubler was angle cut for type-II phase matching at 1064 nm with the dimension of 4×4×8 (mm), and both faces of it were coated for HT at 1064 and 532 nm. The SESAM was grown at low temperature by metal-organic chemical-vapor deposition (MOCVD). It consisted of 25 pairs of GaAs/AlAs quarter-wave Bragg layers with the high reflectivity of 99.5%, and the modulation depth of SESAM was less than 1%.

The laser cavity consisted of five mirrors: the input mirror, flat cavity mirror M1, cavity mirror M2 which were all coated with HR at both 1064 and 532 nm, the output coupler M3 coated with HR at 1064 nm and HT at 532 nm, and a highly reflective SESAM. The radii of curvature for M2 and M3 were 500 and 200 mm, respectively. The arm lengths of four branches, L1, L2, L3, and L4, were approximately 24.5, 35.5, 99.0, and 12.4 cm, respectively. Thus the total length of the cavity should be 171.4 cm. The angle of the folded mirrors was kept at less than 10° in order to reduce the astigmatism in the intracavity spot size. By the $ABCD$ analysis, we calculated the mode radii to be about 257 μm in the laser

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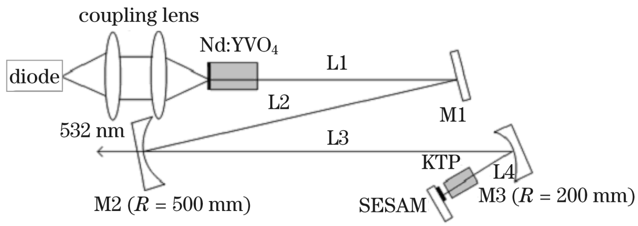

Fig. 1. Configuration of the $Nd:YVO_4$/KTP green laser with a SESAM.

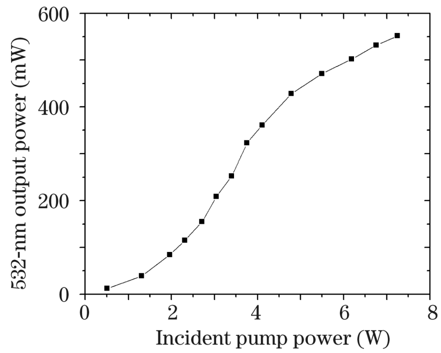

Fig. 2. Dependence of average output power on incident pump power.

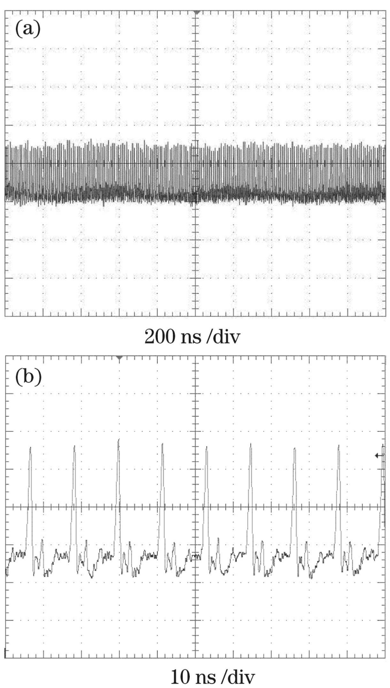

Fig. 3. Pulse trains of CW mode-locked green laser at (a) 200- and (b) 10-ns scales.

crystal and 27 μm on the SESAM.

To examine mode matching, we substituted M1 and the KTP crystal with a flat mirror of 10% transmittance at 1064 nm. With the above laser cavity configuration, the average output of 3.55 W at 1064 nm was achieved at an incident pump power of 9.59 W, corresponding to an optical-optical efficiency of 37.0%, which proves that a good mode matching is achieved with the current cavity design.

The relationship between the 532-nm output power and the incident pump power is shown in Fig. 2. The threshold for generation of CW green light was about 0.11 W.

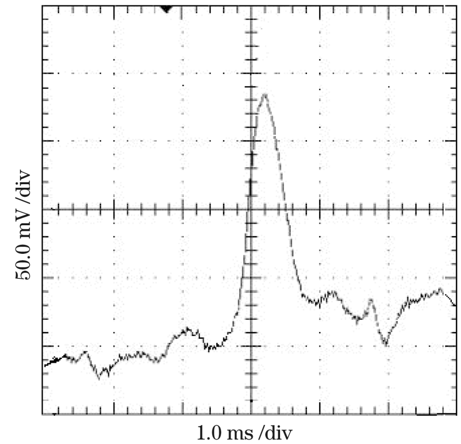

Fig. 4. Autocorrelation signal of CW mode-locked pulse at 1064 nm.

Within the range of the incident power from 1.8 to 3 W, the laser had a Q-switching mode-locked operation regime. When the incident pump power increased to 3 W, the laser pulse switched to CW mode-locked regime. The green laser exhibited stable and clean CW mode-locked pulse train, which was detected by a fast photodiode detector (NEW FOUCS 1623) with a rising time of 2 ns. The maximum average output power of 552 mW was obtained at the incident pump power of 7.25 W. Further increasing the incident power, the KTP reached saturated gain and the output power could not increase any more. The output power fluctuation $\Delta\overline{p}$ of the green laser was tested when the incident pump power was 7.25 W. The green laser power was measured at a time interval of 5 min in 1 h. If the output laser power fluctuation $\Delta\overline{p}$ is calculated by

$$\Delta\overline{p} = \sqrt{\sum_{i=1}^{n} \frac{\left(P_i - \overline{P}\right)^2}{n}}, \quad (1)$$

the instability $\Delta\overline{p}/\overline{p}$ of the green laser is 0.61%.

The CW mode-locked pulse trains at 200- and 10-ns scales were investigated, as depicted in Fig. 3. The repetition rate of 87 MHz was in agreement with the theoretical result which was calculated by $f = c/2l$ (c is the speed of light in vacuum, l is the total length of the cavity). As KTP has mode-locking mechanism, the CW mode-locking pulse of 532 nm is cleaner and more stable than the CW mode-locked pulse of 1064 nm.

Due to the limitation of the instrument, the pulse duration of the 532-nm CW mode-locked pulse cannot be measured. However, the mode-locked pulse duration of 532 nm can be estimated from the mode-locked pulse duration of 1064 nm as $\tau_{532} = \tau_{1064}/\sqrt{2}$[12]. The pulse duration of 1064 nm at the CW mode locked operation was measured by an autocorrelator (FR-103XL). A typical autocorrelation trace of the pulse is shown in Fig. 4. The train width (full-width at half-maximum FWHM) of the trace is about 560 μs. Taking a Gaussian profile, we estimated that the fundamental pulse duration was about 11.9 ps. Thus the pulse width of 532 nm was assumed to be approximately 8.4 ps.

In conclusion, we have successfully demonstrated a passively CW mode-locked intracavity frequency doubled

$Nd:YVO_4$/KTP green laser with SESAM. By using a five-mirror cavity, the 87-MHz CW mode-locked pulse was obtained with the pulse width estimated to be 8.4 ps. The average output power of 552 mW was achieved at the incident pump power of 7.25 W, corresponding to the optical-optical efficiency of 7.6%. The instability of the green laser at the pump power of 7.25 W was 0.61%.

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