

5.3-W Nd:YVO₄ passively mode-locked laser by a novel semiconductor saturable absorber mirror

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We report a diode end-pumped continuous wave (CW) passively mode-locked Nd:YVO₄ laser with a home-made semiconductor saturable absorber mirror (SESAM). The maximum average output power is 5.3 W at the incident pump power of 17 W, which corresponds to an optical-optical conversion efficiency of 31.2% and slope efficiency of 34.7%. The corresponding optical spectrum has a 0.2-nm full width at half maximum (FWHM), and the pulse repetition rate is 83 MHz.

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In recent years, there has been significant interest in passively mode-locked all-solid state lasers with semiconductor saturable absorber mirrors (SESAMs) or saturable Bragg reflectors (SBR)^[1–12]. Passively mode-locked lasers with high average power and high peak power are required for numerous applications, especially involving nonlinear frequency conversion. Broader visible lines, for example red/green/blue (RGB) displays^[1,13], can be obtained via optical parametric oscillator (OPO), pumped by the frequency doubled infrared laser.

Introducing a saturable absorber, the laser is easy to operate in passively *Q*-switching mode-locked (QML)^[14]. Generally, QML is an unwanted regime of operation for most applications. Therefore, a key issue is how to design the laser to suppress the self-*Q*-switching tendency and obtain continuous wave (CW) mode-locked pulses. According to Ref. [14], We used the Nd:YVO₄ as the laser gain medium and designed a long cavity to decrease the repetition rate of pulses. Attractive property of the Nd:YVO₄ relates to its short upper-state lifetime (99 μs), which, combined with its high emission cross section, will minimize the tendency of *Q*-switching dynamics when it is mode-locked with a semiconductor-based slow saturable absorber. Also, the broad absorption band (~12 nm) centered at 808 nm makes diode pumping possible and at the same time reduces the requirement for control of pump wavelength. The mode radii in the laser crystal and on the SESAM also were carefully considered.

In this paper, we presented a high average output power CW passively mode-locked Nd:YVO₄ laser with a novel home-made SESAM: surface-state type of SESAM. The laser delivered CW mode-locking (CWML) pulses with an output power of 5.3 W and a repetition rate of 83 MHz. The optical spectrum was measured to be 0.2

nm.

Our experimental setup is shown in Fig. 1. The laser crystal was pumped by high-brightness fiber-coupled laser diode arrays at 808 nm (Lingyun Photoelectric System Co., Ltd), which provided an output power up to 24 W. The fiber had a core diameter of 400 μm and a numerical aperture (NA) of 0.22. A 1:1 coupling lens with 75% coupling efficiency was used to re-image the pump spot into the laser crystal. The laser crystal was an a-cut Nd:YVO₄ (with a Nd³⁺ concentration of 0.5 at.-% and dimensions of 3×3×5 (mm)) wrapped with indium foil and tightly mounted in a water-cooled copper holder. The temperature of the holder was maintained at 14 °C during the operation. The pump surface of Nd:YVO₄ was coated with high-reflection (HR) for operating wavelength of 1064 nm and high antireflection (AR) for pump wavelength of 808 nm. The other surface was AR coated for 1064 nm. The cavity consisted of four mirrors (including the SESAM) and the laser crystal. The output coupler (OC) was a plane mirror with 10% transmissions, giving a double-passing output coupling of 20%. The radii of curvature of *M*₁ and *M*₂ were 1 m and 200 mm, respectively. The two curved mirrors can

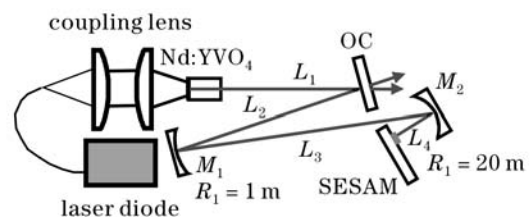


Fig. 1. Experimental setup of the mode-locked Nd:YVO₄ laser.

control the mode radius in the laser crystal and on the SESAM in a simple manner. The resonator was designed to easily allow mode matching with the pump laser, to provide the proper spot size on the SESAM, and to have low sensitivity to both misalignment and thermal lensing. Carefully designed the cavity, the arm lengths of four branches, L_1 , L_2 , L_3 and L_4 , approximated to 22, 31.5, 116, and 10 cm, respectively, the total cavity length was ~ 180 cm, corresponding to a round-trip time of ~ 12 ns. The laser mode radii were calculated to be about $160 \mu\text{m}$ in the laser crystal and $30 \mu\text{m}$ on the SESAM at the thermal lens focus length of 20 cm, based on the standard ABCD matrix calculation.

We used a surface-state type of semiconductor saturable absorber mirrors^[15] to achieve CWML. The absorption layer was a 15-nm $\text{In}_{0.25}\text{Ga}_{0.75}\text{As}$ quantum well (QW), grown on the top of AlAs/GaAs Bragg mirror. The Bragg mirror contained 22 pairs of quarter-wave layers. By placing the QW close to the air interface, the carrier recombination was accelerated through tunneling to the surface states. A very thin (2 nm) GaAs was added on the top of the QW as a protection layer. The growth of the absorption of the SESAM was grown at normal temperature (700°C) by metal organic chemical vapor deposition in order to decrease the non-saturable loss, which would lead to the high threshold for anti-laser-destroy. The SESAM was glued on a water-cooled copper disk and the temperature was maintained to 14° . Figure 2 is the reflection spectrum for the surface-state type of semiconductor saturable absorption mirror.

Preliminary CW experiments with a HR mirror at 1064

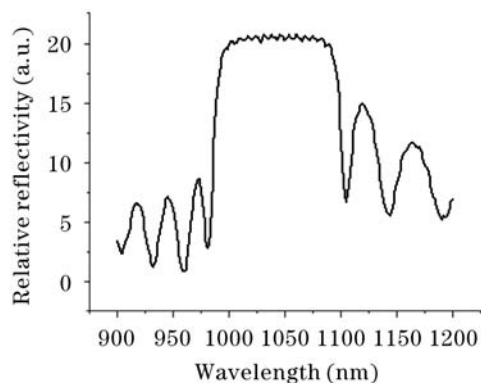


Fig. 2. Reflection spectrum of surface type semiconductor saturable absorption mirror.

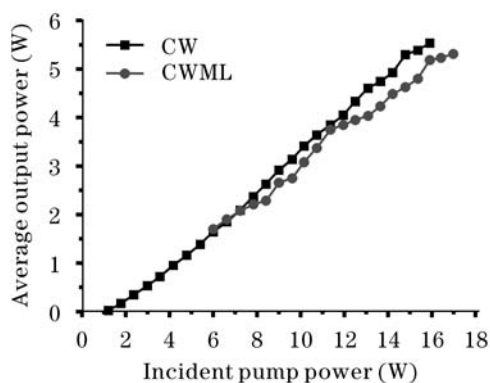


Fig. 3. Output power in CW operation and in CW passively mode-locked regime.

nm substituted for the SESAM were conducted. The CW output behavior of the laser was investigated, as shown in Fig. 3. We obtained TEM_{00} operation with as much as 5.5 W at the incident pump power of 16 W, by simply increasing the pump power without adjusting the distance L_4 to optimize mode matching with different pump powers. The optical-optical conversion efficiency was 34.4% and the slope efficiency was 39.4%. The pump threshold was about 1 W of incident pump power.

Inserting the SESAM into the cavity, we easily obtained the CWML operation. The dependence of average output power on the incident pump power was investigated as shown in Fig. 3. The CWML threshold was slightly below 5.5 W of incident pump power. At the incident pump power of 17 W, the CWML average output power was up to 5.3 W, corresponding to an optical-optical conversion efficiency of 31.2% and slope efficiency of 34.7%. Compared with the CW operation, the CWML average output power was only slightly decreased, indicating that the loss of the SESAM is small. When we further increased the pumping power, the SESAM was damaged. The damaged threshold fluence of the SESAM was calculated to be about $11 \text{ mJ}/\text{cm}^2$. This may be due to the small laser mode radius on the SESAM and large pulse energy. It is reasonable to expect that if we use a larger radius of curvature of folding mirror to replace the M_2 , the output power may be higher than the present results.

The pulse train was recorded by a digital phosphor oscilloscope (Tektronix 5104B; 5Gsamples/s, 1-GHz bandwidth) with a fast PIN photodiode. Figure 4 shows the CWML pulse train of the Nd:YVO₄ laser with SESAM. We can see that the pulse repetition rate is 83 MHz and the pulse interval is 12 ns.

The CWML laser spectra were measured with a fiber

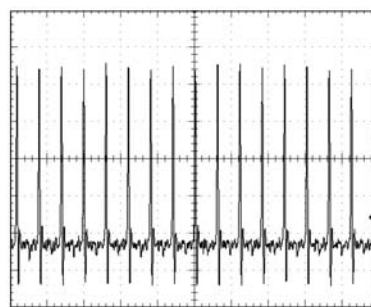


Fig. 4. CW mode-locked train of the Nd:YVO₄ laser with SESAM.

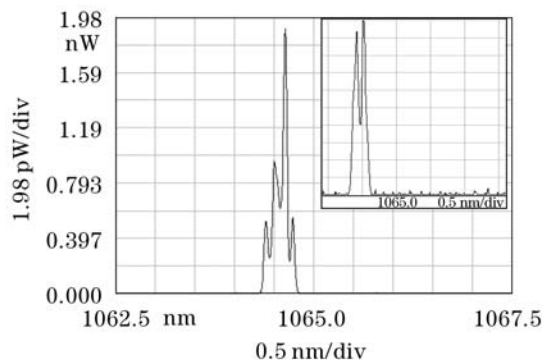


Fig. 5. Spectra of CWML and CW (inset) operations.

coupled spectrum analyzer (Agilent 86142B, USA) as shown in Fig. 5. The wavelength was centered at 1064.6 nm with full width at half maximum (FWHM) of 0.2 nm. The inset is the CW operation optical spectrum. Figure 5 shows the different spectral performances of CW and CWML operations. The spectrum feature presented longitudinal spacing due to the etalon effect. Compared with the CW spectrum, the number of the minor peaks of the CWML spectrum was increased because the mode-locking operation widened the laser spectrum. The pulse width was not measured limitedly in our experiment. But we can know the transform limit pulse width was approximate 9 ps by Fourier transform.

In conclusion, we have demonstrated a diode-end-pumped passively mode-locked Nd:YVO₄ laser with a SESAM. The average output power up to 5.3 W was obtained at the incident pump power of 17 W for the pulse repetition rate of 83 MHz. The optical-optical conversion efficiency was 31.2% and the slope efficiency was 34.7%. The spectral bandwidth was measured to be 0.2 nm.

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