LD end-pumped 1.5 W passively CW mode-locked $Nd:YVO_4$ laser

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In order to get stable continuous wave (CW) mode-locked (ML) laser, conventionally, the laser cavity was designed to reach very small mode radius in the laser crystal to make the laser material saturated. While for the laser diode (LD) end pumped $Nd:YVO_4$ without fiber coupling transmission, as long as choosing the appropriate short focus lens and making the focus area in front of the $Nd:YVO_4$ small enough, we found even large cavity mode volume can make the laser material saturated. In addition, relatively large cavity mode volume can make high power output with single mode come true. Ideal beam quality without high order transverse mode oscillating, the CW ML state turned to be very stable. Accordingly, relatively large mode volume in the laser crystal was designed with semiconductor saturated absorber mirror (SESAM), over 1.5-W CW ML output with near diffraction limited was acquired. The optical-to-optical conversion efficiency reached 30%.

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In 1992, Keller brought semiconductor saturated absorber mirror (SESAM) to passively continuous wave (CW) mode-locked (ML) laser[1], since then, super-short pulse laser faced a new age. Compared with actively mode-locked laser and passively mode-locked dye laser, the passively mode-locked laser with SESAM showed many advantages such as compact, simple, robust, and inexpensive etc.[2−4]. Furthermore, all solid-state picosecond (ps) mode-locked lasers with high average output power and good beam quality were required for many applications such as medicine, material processing, laser show, large-scale laser display[5] and so on. Especially in nonlinear frequency conversion, with sufficiently high peak powers (several thousand watts) we can achieve very high efficiency wavelength conversion (> 50%) by single-pass interactions in some appropriate nonlinear crystals[6]. This result can extend the wavelength to visible, ultraviolet or infrared band to meet more and more various applications. In addition, regenerative and power amplifiers can amplify the energy or power amplified to more than 10^8.

In this letter we describe stable passively mode-locked of $Nd:YVO_4$ laser with a SESAM. This research resulted in the generation of 12-ps duration pulse at the wavelength of 1064 nm with a repetition rate of 120 MHz, average power of 1.5 W, and peak power of 1.46 kW. This laser is reliable, stable, and easy to generate CW ML. With 4 hours continuous work, the laser maintains stable CW ML, and the waveform of the mode-locked pulse had no change.

Figure 1 shows the schematic of experimental setup. The pump source is a diode laser with the max power of 5 W. A convex lens with 6-mm focus length is used to focus the pump beam into the gain medium so as to achieve small enough pumped area. Because the absorption coefficient of $Nd:YVO_4$ is very large, the pump beam can be absorbed easily, that is to say, we need not worry about the emanative remanent pump beam by limited focus length and off-focus. To fit the pump wavelength for the maximum absorption by the gain medium, we used a semiconductor cooling plate to control the temperature of the diode laser at 22 °C. The gain medium is α-cut $Nd:YVO_4$ crystal with 1.0 at.-% neodymium doping, and size is 3×3 (mm) in surface aperture and 3 mm in length. The left side of the $Nd:YVO_4$ is coated antireflective (AR) at 808 nm and high-reflective (HR) at 1064 nm, the other side of crystal is coated AR at 808 nm and 1064 nm to decrease the optical loss and avoid potential etalon effect. The absorption coefficient at 808 nm wavelength is 31.4 cm^{-1}. To alleviate the thermal load, the crystal is wrapped by indium foil and packed inside a copper holder, which is cooled by another thermal energy converter (TEC). The mirror M_1 is coated with HR (> 99.8%) at 1064 nm with 500 mm curvature; one of the mirror M_2 surfaces is coated AR. Both of the lense are coated AR at 1064 nm with 50-mm focus length, which is used to focus the laser beam on the SESAM, and the spot size is calculated about 40 μm in diameter. The SESAM's modulation depth ΔR equals 1.0%, non-saturable loss equals 0.6%, saturation fluence equals 70 $\mu J/cm^2$ and the relaxation time constant is

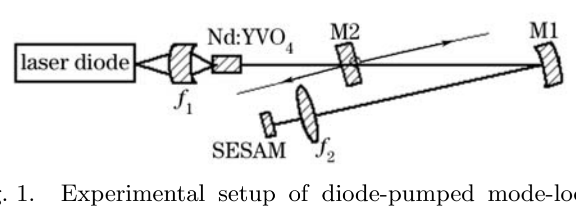

Fig. 1. Experimental setup of diode-pumped mode-locked $Nd:YVO_4$ laser.

less than 10 ps.

According to the theory of Q-switching stability limits of CW passive mode locking[7], the minimum pulse energy $E_{\rm p}$ for stable CW mode locking can be obtained by

$$E_{\rm p} = \sqrt{F_{\rm satYVO_4} \cdot A_{\rm YVO_4effl} \cdot F_{\rm satA} \cdot A_{\rm sesam} \cdot \Delta R}, \quad (1)$$

where $F_{\rm satYVO_4} = h\nu/\sigma N$ denotes the saturation fluence of the gain medium with a lasing frequency ν, σ is the stimulated emission cross section, and $N = 2$ is used to reflect the average times in the standing-wave in a linear cavity; $A_{\rm YVO_4}$ denotes the spot size on the Nd:YVO_4; $F_{\rm satA}$ denotes the saturation fluence of the saturable absorber with a modulation depth of ΔR,

$$\nu = \frac{c}{\lambda}, \quad (2)$$

$$\sigma_{\rm YVO_4emL} = 25 \times 10^{-19} \ \ {\rm cm}^2, \quad (3)$$

$$F_{\rm satYVO_4} = \frac{hc}{\lambda N \sigma_{\rm YVO_4emL}}, \quad (4)$$

$$A_{\rm sesam} = \pi \times 0.0025^2 \ \ {\rm cm}^2. \quad (5)$$

The saturation fluence of Nd:YVO_4 is estimated to be $F_{\rm satYVO_4} = 0.037$ J/cm^2, $A_{\rm sesam}$ denotes the spot size on SESAM which was estimated to be 40 μm, the saturation fluence of the absorber was estimated to be $F_{\rm satYVO_4} = 70$ μJ/cm^2, and the modulation depth of the saturated absorber was $\sim 1\%$. Thus the estimated minimum pulse energy for stable mode locking was around 55 nJ. The experiment minimum pulse energy for stable

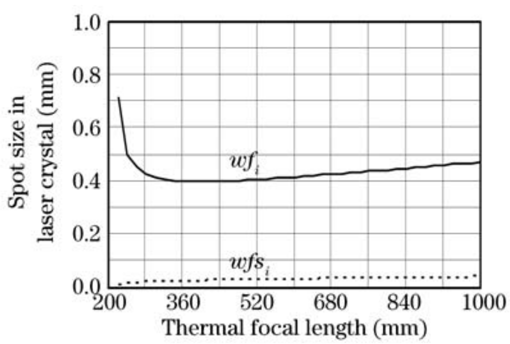

Fig. 2. Fundamental spot size in the middle of the laser crystal wf_i and SESAM wfs_i alters with the thermal focal length.

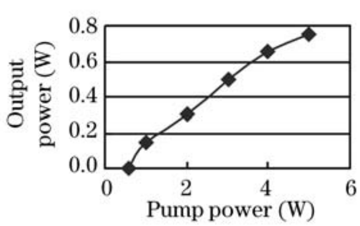

Fig. 3. Average output power versus pump power for mode locked Nd:YVO_4 laser.

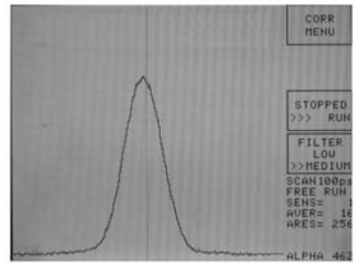

Fig. 4. CW ML waveform. Full-width at half-maximum (FWHM) is 16.8 ps.

mode locking could be estimated by

$$E_{\rm p} = P_{\rm out} \frac{1 + (1 - T_{\rm oc})}{T_{\rm oc} f_{\rm rep}}, \quad (6)$$

where $f_{\rm rep}$ denotes the repetition rate frequency $\sim$120 MHz, the average output power $P_{\rm out}$ was about 1.5 W and the output coupler $T_{\rm oc}$ was 8%. Figure 2 describes the fundamental spot size in the middle of the laser crystal wf_i and SESAM wfs_i alters with the thermal focal length. The mode radius in the laser crystal keeps large than 0.4 mm and wfs_i smaller than 0.02 mm.

The output power as a function of pump power is plotted in Fig. 3. When the pumping power was increased to 5 W, we obtain output power of 0.75 W from each of the output direction and the whole power is 1.5 W. The optical-optical efficiency is 30%. The CW ML starts at 0.15 W from one direction.

The CML waveform is showed in Fig. 4, the pulse trains are stable. The pulse duration is about 12 ps.

In summary, we report a CW passively mode-locked Nd:YVO_4 laser at 1064 nm. A SESAM is used in the laser to generate pulses of 12 ps with a repetition rate of $\sim$120 MHz. An average power of 1.5 W is obtained with an optical-optical efficiency of $\sim$30%. The result revealed that appropriate large cavity mode volume can achieve both high output power and stable CW ML.

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