Compact high-power mode-locked Nd:YVO_4 picosecond laser using multiple-pass cavity

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Received March 19, 2013; accepted May 13, 2013; posted online July 18, 2013

A stable self-starting mode-locked Nd:YVO_4 laser with a Herriott-type multiple-pass cavity (MPC) operating at 1 064 nm is demonstrated. An in-band 880-nm laser diode is used as an end-pump and a semiconductor saturable absorber mirror (SESAM) is used for passive mode locking (ML) and providing pulse durations of 14 ps. At a pump power of 26.4 W, the maximum average output power is as high as 10.5 W at a repetition rate of 22 MHz, which corresponds to a single pulse energy of 0.48 μJ. Optical-to-optical conversion efficiency is as high as 39.8% at the maximum output power with a slope efficiency of 55.2%.

OCIS codes: 140.4050, 140.3480, 140.3580.

doi: 10.3788/COL201311.081401.

Compact high average-power picosecond lasers are attractive in many fields, such as physics, military science, and biology[1−3]. Because of their important uses in a wide range of applications, solid-state pulse lasers, particularly Nd:YVO_4 picosecond lasers that can achieve stable, high power outputs by the large stimulated-emission cross-section of their gain medium, have become popular research topics. Several methods have been used to increase the average output power and single-pulse energy of Nd:YVO_4 lasers. For example, external amplifiers outside the oscillator are used to enhance the output power and energy. An 880-nm in-band pump is used to reduce thermal effects, and the multiple-pass cavity (MPC) technique is used to simplify devices and increase pulse energy[4,5].

To overcome the weak thermal conductivity of Nd:YVO_4 crystals in high-power operation with traditional 808-nm pump, 880-nm laser diode (LD) is used to reduce thermal effects and quantum defects in the laser crystal[6]. Nd:YVO_4 passively mode-locked lasers pumped at 880 nm have been intensively investigated and improved in recent years. To the best of our knowledge, the highest average output power reported thus far is 56 W at a 33 ps pulse width and 110 MHz[7]. The Herriott-style MPC is a useful technique for increasing the single-pulse energy of lasers while maintaining their simplicity. The MPC extends the cavity optical path by allowing the laser beam to bounce through the short multiple-pass cavity, thereby simultaneously keeping the setup compact and supporting high single-pulse energies and low repetition rates[8]. MPC is widely used in Nd:YVO_4 picosecond lasers because of these advantages[9]. A maximum output power of 4.1 W with 13 ps pulse width at 4.1 MHz was previously reported[10].

The present study demonstrates a compact 880-nm pumped Nd:YVO_4 picosecond laser featuring an MPC and SESAM. During continuous wave mode locking (CWML) operation without the MPC, the maximum output power achieved is 12.1 W with an absorbed pump power of 26.4 W, corresponding to a slope efficiency of 61.2%. The pulse width is 16 ps and the pulse repetition rate is 64 MHz. During CWML operation with the MPC, the maximum output power is 10.5 W with a pump power of 26.4 W, corresponding to a slope efficiency of 55.2%. The pulse width is 14 ps and the repetition rate is 22 MHz. Firstly, research on 880-nm in-band pumped high power CWML Nd:YVO_4 lasers without MPC was carried out. A schematic diagram of the laser cavity is shown in Fig. 1. A fiber coupled diode laser with a maximum output power of 30 W and central emitting wavelength of 880 nm was used as the end-pump source. The fiber had a core diameter of 200 μm and numerical aperture (NA) of 0.22. A series of lenses with an image ratio of 1:2 was used to focus the pump beam in the crystal. The M1 was a dichroic mirror with highly reflective (HR) and anti-reflective (AR) coatings at 1 064 and 880 nm, respectively. The 0.5-at.% Nd:YVO_4 crystal had dimensions of 3 × 3 × 5 (mm) and was coated on both faces with a AR film at the lasing and pumping wavelengths. The concave mirrors M2, M3, and M5 were coated with a HR film at 1 064 nm with radii of curvature of 200, 500, and 500 mm, respectively. An output coupler (OC) that had a transmission of 30% was used as an end mirror, while another end was optional for CWML operation either with or without the MPC.

The total cavity length was 2.3 m, corresponding to a repetition rate of 64 MHz. The dependence of the laser output power on the incident pump power in CWML reg-

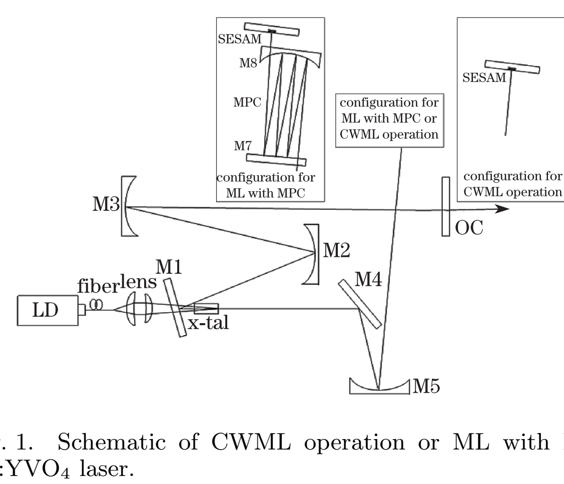

Fig. 1. Schematic of CWML operation or ML with MPC Nd:YVO_4 laser.

imes is illustrated in Fig. 2. The maximum output power is 12.1 W at a pump power of 26.4 W, corresponding to a slope efficiency of 61.2%. The measured output pulse duration is 16 ps (FWHM) at the maximum output power, assuming that the pulses exhibit a sech^2-shaped temporal intensity profile. Standard position-beam-radius measurements show beam qualities of M_x^2 =1.07 and M_y^2 =1.09.

To scale up the single-pulse energy of the abovementioned CWML laser, we inserted a Herriott-type MPC[8] in one arm to extend the cavity length. The cell was made up of a flat HR mirror (M7) and a concave mirror (M8) with a radius of curvature of 1 090 mm, as illustrated in Fig. 1. According to Eqs. (1) and (2), on the basis of theory discussed in Ref. [8], the Q parameter of the laser cavity does not change when the overall transmission matrix of the cell is a unit matrix:

$$N\theta = M\pi, \tag{1}$$

$$\cos\theta = \frac{A+D}{2}, \tag{2}$$

where N represents the bouncing times in the MPC and N and M could be any integer. In the present study, N=10 and M=3. The distance between M7 and M8 is 22.5 cm and the overall optical length in a single trip

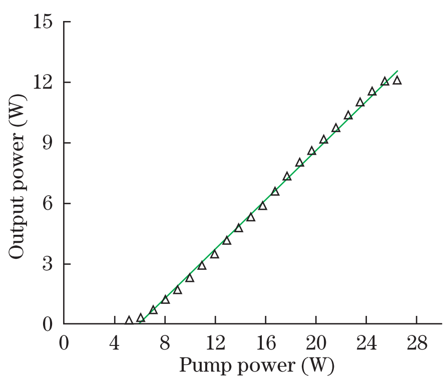

Fig. 2. (Color online) Output power as function of pump power during CWML operation.

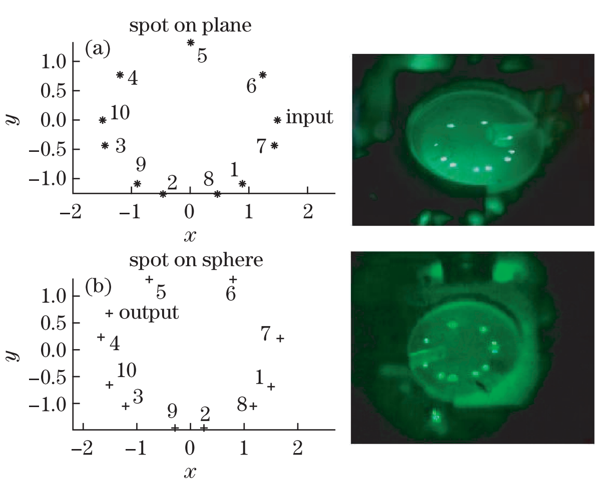

Fig. 3. (Color online) (a) Spot pattern on M7 compared with the actual distribution; (b) spot pattern on M8 compared with the actual distribution.

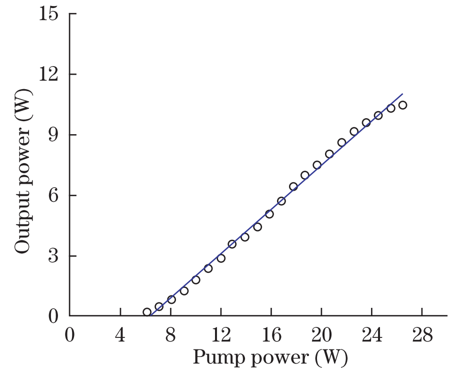

Fig. 4. (Color online) Output power as function of pump power in the mode-locked Nd:YVO_4 picosecond laser with a MPC.

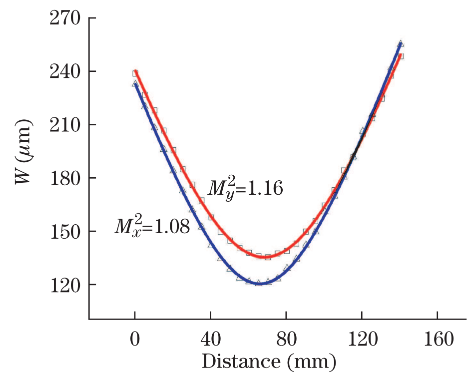

Fig. 5. (Color online) M^2 factor of the output laser beam in the mode-locked Nd:YVO_4 picosecond laser with a MPC.

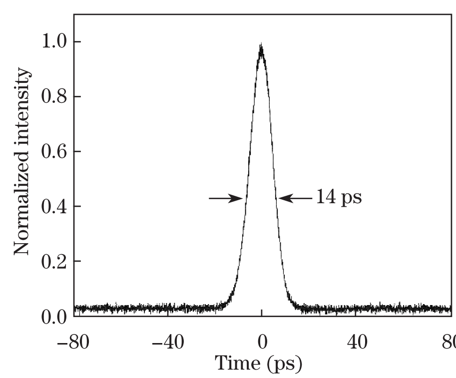

Fig. 6. (Color online) Autocorrelation signals of pulse output from the mode-locked Nd:YVO_4 picosecond laser with a MPC.

through the cell is 4.5 m. Figure 3 shows simulation results of spot patterns on both mirrors as well as images of their actual distribution. In the figure, a total of 22 spots on the two mirrors are shown, including input and output spots, which should not be observed during actual operation.

When the cell is inserted, the total cavity length becomes 6.8 m. When the Q parameter of the cavity is retained, the laser operates at a repetition rate of 22 MHz in CWML. By optimizing the alignment, a maximum output power of 10.5 W is achieved with a pump power of 26.4 W, as shown in Fig. 4. Beam quality measurements (Fig. 5) reveal that the values of M^2 are less than 1.2 in both directions, which implies a near-diffraction limit beam quality. The autocorrelation signal shows that the output pulse has a width of 14 ps, as illustrated in Fig. 6.

Although the average output power decreases from 12.1 to 10.5 W corresponding to a 13% loss, the pulse energy considerably increases from 0.19 to 0.48 μJ. Minimal deterioration in the beam quality, wherein M_x^2 changes from 1.07 to 1.08 and M_y^2 changes from 1.09 to 1.16, is observed, which still indicates a near-diffraction limit laser beam. Comparing the pulse durations obtained during MPC CWML operation (14 ps) and non-MPC CWML operation (16 ps), slight changes are observed and even shorter pulses are obtained. Based on previous research done by Kurtner *et al.*[11], higher pulse energy in the cavity may result in reduction in pulse width.

In conclusion, we develop a diode-pumped passively mode-locked picosecond Nd:YVO_4 laser with a MPC. Laser pulses with a width of 14 ps in hyperbolic secant profile fitting are obtained at a repetition rate of 22 MHz. A maximum output power of 10.5 W is obtained at the maximum pump power of 26.4 W, corresponding to an optical-to-optical efficiency of 39.8% and a slope efficiency of 55.2%.

This work was supported by the National "973" Program of China (No. 2011CB808101) and the National Natural Science Foundation of China (No. 11127901).

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