Single output LD end-pumped passively mode-locked Nd:YVO_4 laser with semiconductor saturable absorber mirror*

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A quarter-wave plate and the thin film polarizer (TFP) are used for the LD end-pumped passively mode-locked Nd:YVO_4 laser with semiconductor saturable absorber mirror (SESAM) to obtain a single beam output with a total power of 4.8 W. An optical–optical efficiency is achieved to be 24% for a stable CW mode-locking operation at 1064 nm, with a pulse repetition rate of 70 MHz and pulse width of 16 ps. The multipulse in the pulse sequence is eliminated for reaching a peak power as high as 4 kW.

Keywords: single output, passively mode-locked, semiconductor saturable absorber mirror

PACC: 4260, 4260B, 4260D, 4280W

1. Introduction

Recently, passively mode-locked solid-state laser produced picosecond pulses have been found to have many applications in the fields of laser display, nonlinear frequency conversion and high precision micromachining.[1] Some potential applications are emerging with the further development of solid-state lasers and new mode locking techniques, particularly Kerr lens and semiconductor saturable absorber mode-locking.[2] The saturable absorber can be optimized independently of the cavity design, allowing successful mode locking to be achieved in a broad range of solid-state lasers and cavity designs,[3,4] and the semiconductor saturable absorber mirror (SESAM) which is a saturable absorber integrated into a mirror structure is mostly used as an end mirror of a standing wave laser cavity. In this condition, the laser cannot be pumped through the SESAM, which means that the laser cannot be output from the SESAM. Thus there appear some ways to design the laser with a single output.[5−8] Nd:YVO_4 has a large stimulated emission cross section and high absorption coefficient for diode pumping, and it has been used as a laser crystal for continuous-wave,[9] Q-switched,[10] and mode-locked[11] lasers.

In the present paper, we demonstrate a passively mode-locked solid state laser with SESAM, in which a polarization output coupling is conveniently implemented,[12] with a quarter-wave plate located between the SESAM and the polarizer, and a single beam carrying the total power is preferred along with end-pumping. From this experiment we obtain a CW mode-locked pulse at 1064 nm with a pulse width of 16 ps, repetition rate of 70 MHz, single output average power of 4.8 W, and calculate the peak power to be about 4 kW.

2. Experimental setup and results

Figure 1 shows a passively mode-locked laser setup with SESAM. The high-brightness fibre-coupled laser diode at 808 nm, cooled by a thermal energy converter (TEC), was chosen as a pump power source, which provided an output power of up to 30 W. The fibre has a core diameter of 200 μm and a numerical aperture (NA) of 0.22. A focusing lens was used to reimage the pump beam with a waist diameter of 200 μm into the laser crystal. The a-cut Nd:YVO_4 used in our experiment has an Nd^{3+}-doping concentration of 0.3 at% which is $3\times3\times9$ mm^3 and wedged. The left side of the Nd:YVO_4 is coated with an antireflective (AR) film at 808 nm, the other side of crystal is AR-coated at 808 nm and 1064 nm. To reduce the thermal load, the crystal was wrapped by indium foil and packed inside a copper holder. The laser diode

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and crystal were cooled by 15 °C circulating water. M1 was a flat mirror AR-coated at 808 nm and HR-coated at 1064 nm, while M3 was also a flat mirror HR-coated at 1064 nm. M2 and M4 were HR-coated at 1064 nm, with the radii of curvature of 1000 mm and 248 mm, respectively. A SESAM, made by Batop GmbH in Germany, was used as an end mirror of the cavity and simply mounted on a small copper heat sink without active cooling. A quarter-wave plate was located between the SESAM and the thin film polarizer (TFP) so that a single beam carrying the total power was preferred along with end-pumping.

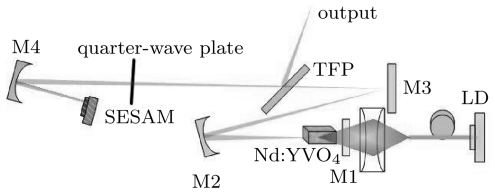


Fig. 1. Experimental setup of the LD-pumped passively mode-locked Nd:YVO_4 picosecond laser with SESAM.

Output couplers with different transmissivities can be obtained by adjusting the angle of the quarter-wave plate. For stable CW mode-locking, the criterion for stable mode-locking laser with an SESAM is given by[13]

$$\frac{2LP_{\rm out}}{cT} \geq \pi\sqrt{F_{\rm sat,a}\omega_{\rm a}^2 F_{\rm sat,g}\omega_{\rm g}^2 \Delta R}, \qquad (1)$$

where L is the length of the cavity, $P_{\rm out}$ is the output power of the laser, c is the speed of light in vacuum, and T is the output coupler transmission, $\omega_{\rm a}$ and $\omega_{\rm g}$ are the values of the intensity radius of the laser beam at the SESAM and in the gain medium, respectively. $F_{\rm sat,a}$ and $F_{\rm sat,g}$ are the saturation fluences of the SESAM and the gain medium, respectively.

In order to obtain the stable CW mode-locking, inequation (1) must be fulfilled, by, for instance, increasing the length of the cavity, reducing the transmissivity of the output coupler using the quarter-wave plate, and reducing the values of the intensity radius of the laser beam at the SESAM and crystal. It should be noted that the intracavity pulse fluence should be kept three to five times the saturation fluence of the SESAM, since it is hard to obtain mode-locking if the value of the impulsion fluence is too small. During the experiment, the value of the impulsion fluence was controlled by adjusting the value of the intensity radius of the laser beam at the SESAM ($\omega_{\rm a}$).

To satisfy the mode-locking conditions, we selected the cavity length $L = 2.12$ m and adjusted the TFP to obtain the output power $P_{\rm out} = 4.8$ W. The energy of a mode-locked pulse in the cavity is defined as $E_{\rm P} = 2LP_{\rm out}/cT$, so the minimum intracavity pulse energy is $E_{\rm P,c} = \pi\sqrt{F_{\rm sat,a}\omega_{\rm a}^2 F_{\rm sat,g}\omega_g^2 \Delta R}$. The laser operates in Q-switched mode locking (QML) with $E_{\rm P} < E_{\rm P,c}$, while the laser operates in continuous-wave mode locking (CWML) with $E_{\rm P} > E_{\rm P,c}$. In our experiment, the saturation fluences of the SESAM and the gain medium are $F_{\rm sat,a} = 70$ μJ/cm^2, and $F_{\rm sat,g} = 0.12$ J/cm^2 respectively. The calculated profile of the beam (TEM00 mode radius) in the laser resonator is shown in Fig. 2, based on the standard ABCD matrix. The laser mode radii on the SESAM and in the gain medium are 26 μm and 240 μm, respectively, at a thermal lens length of 145 mm. The modulation depth of the SESAM is 1.2%. Hence, the minimum intracavity pulse energy $E_{\rm P,c}$ is 0.06 μJ in our experiment.

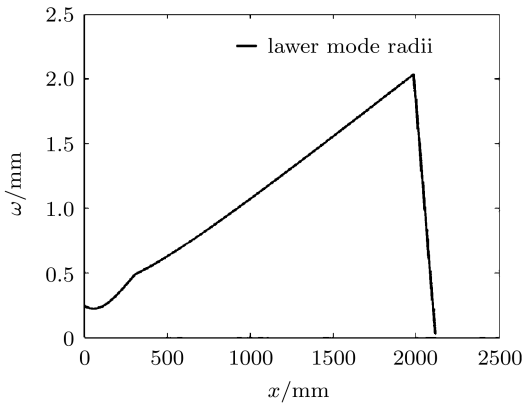


Fig. 2. Calculated profile of the beam (TEM00 mode radius) in the laser resonator.

In the experiment, the high output power and the short pulse width of the CWML pulses are expected to be obtained. The laser crystal Nd:YVO_4 is very close to the end mirror M1 to enhance the spatial hole-burning (SHB) and shorten the pulse width.[14] At first, no output coupler was used to obtain the stable CWML pulses, and then a quarter-wave plate was located between the SESAM and the thin film polarizer (TFP) to keep the transmissivity of the output coupler adjusted continuously. With the quarter-wave plate, the intracavity pulse energy can be controlled to obtain high power without damaging the SESAM. With a pump power of 15 W, stable CW mode-locking operation was realized, achieving an average output power of 4.8 W at a pump power of 20 W, corresponding to an optical–optical efficiency of 24% as shown in Fig. 3.

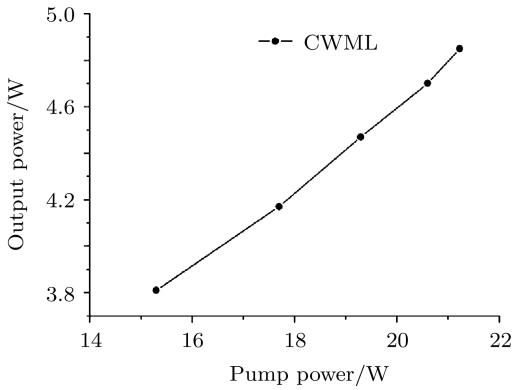


Fig. 3. Output power in the CW passively mode-locked regime.

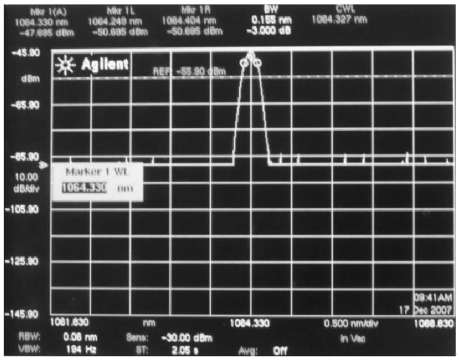


Fig. 4. Optical spectrum centred at 1064 nm, with an FWHM of 0.155 nm.

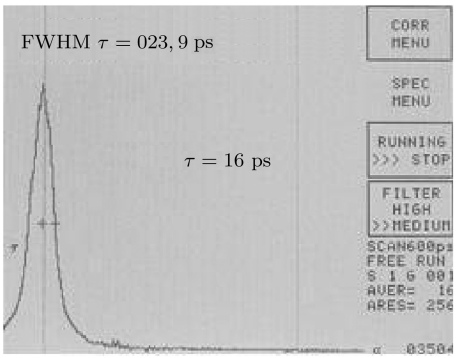


Fig. 5. Measured autocorrelation trace without multipulse.

When the stable mode locking was captured, the repetition of the impulse sequence was measured to be 70 MHz by a digital oscilloscope. The spectrum width of the output beam was 0.155 nm as shown in Fig. 4, corresponding to 41 GHz. The pulse width was measured by using an autocorrelator made by the APE Company (Germany), and figure 5 shows the profile of an autocorrelation signal with an FWHM of 23.9 ps in a range of 150 ps. However, in a range of 600 ps, we found that there was a multipulse induced by the F-P effect generated in the laser crystal, which reduced the peak power of the output laser. Therefore we made the laser crystal inclined or wedged to avoid the multipulse. Figure 5 shows the pulse without multipulse with an FWHM of 23.9 ps. Taking a hyperbolic secant (sech2), we estimated the pulse duration to be $\tau = 16$ ps.

3. Conclusion

We use a quarter-wave plate and thin film polarizer (TFP) in the LD pumped passively mode-locked solid state laser to obtain the single beam output with a total power of 4.8 W. The optical–optical efficiency is achieved to be 24% for a stable CW mode-locking operation at 1064 nm, with a pulse repetition rate of 70 MHz, pulse width of 16 ps, and spectrum width of 0.155 nm. The multipulse in the pulse sequence is also eliminated for achieving a peak power of 4 kW.

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