Periodic adjustment of the position of a laser beam spot on a semiconductor saturable absorber mirror in a passively mode-locked solid-state laser*

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A laser diode end-pumped passively mode-locked Nd:YVO_4 solid-state laser with a semiconductor saturable absorber mirror (SESAM), in which the intracavity laser beam spot on the SESAM can be adjusted periodically, is investigated. Inserting a rectangular prism (RP) into the laser cavity is a promising approach towards the goal of periodically moving the position of the focus spot of the intracavity pulse on the SESAM surface to avoid the long-time irradiation of the laser beam on the same position, thereby solving a series of problems caused by damage to the SESAM and greatly prolonging its usage life. The adjustment of the rectangular prism in the laser cavity does not break the stable continuous wave (CW) mode-locked condition. The laser generates a stable picosecond pulse sequence at 1064 nm with an output power of 3.6 W and a pulse width of 14 ps. The instabilities of the output power and the pulse width are 1.77% and 4.5%, respectively.

Keywords: mode-locked laser, rectangular prism, Nd:YVO_4, semiconductor saturable absorber mirror

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1. Introduction

Owing to developments in ultrafast laser technology, a pulse sequence with ultrashort duration, high repetition rate and high peak intensity can now be generated from mode locking.[1,2] A diode-pumped passively mode-locked high power laser has widespread applications in nonlinear frequency conversion and high precision micro-machinning.[3,4] An end-pumped passively mode-locked solid-state Nd^{3+} laser with a saturable absorber is a promising approach toward these goals.[5,6] However, an important issue is how to avoid damage to the saturable absorber in passively mode-locked high-power lasers. Paschotta *et al.*[7] demonstrated that two possible causes for the damage were thermal and non-thermal effects, particularly in the presence of Q-switching instability. There is another cause of laser-induced damage: the surface behaviour of many optical elements, such as the semiconductor saturable absorber mirror (SESAM), under the irradiation of an intensive laser beam will decrease as the duration of the irradiation time increases. The higher the incident laser beam intensity is, the faster it degrades. The aggravation of the surface behaviour is the so-called laser-induced damage.[8]

We can reduce the intracavity energy, enlarge the mode area of the intracavity pulse on the SESAM and use a low saturation fluence of the SESAM to avoid thermal and non-thermal damage.[7] However, with these methods we cannot change the position of the beam spot on the SESAM. When a laser has been in use for a long time, laser-induced damage is unavoidable and it also reduces the operating life of the SESAM. The effect of the laser power density on the surface of the SESAM is a very important factor in the practical application of passively mode-locked lasers. For this reason, a method for prolonging the usage life of optical elements by using a continuous motion of the optics when a laser beam passes through them is reported in U.S. Patent 5825562.[8]

In this paper, we propose a simple and practicable method to change the relative position between the intracavity laser beam and the SESAM under the irradiation of a laser diode (LD) end-pumped passively mode-locked Nd:YVO_4 solid-state laser. Inserting a rectangular prism (RP) into the laser cavity is

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a promising approach towards this goal. Using this method to change the relative position between the intracavity laser beam and the SESAM, which periodically moves the position of the focus spot of the intracavity pulse on the SESAM surface and avoids the long-time irradiation of the intracavity pulse on the same position, can solve a series of problems caused by damage to the SESAM and prolong its usage life greatly. In addition, it does not break the stable continuous wave (CW) mode-locked condition in the laser cavity or increase loss in it. Then a stable picosecond pulse sequence is generated at 1064 nm with an output power of 3.6 W, a repetition rate of 86 MHz and a plusewidth of 14 ps. The instabilities of the output power and the pulse width are 1.77% and 4.5%, respectively.

2. Experimental setup

Based on the above discussion, we aim to design a method to change the relative position between the intracavity laser beam and the SESAM in the cavity. A simplified model of the passively mode-locked solid-state laser with an SESAM is shown in Fig. 1. A feature of the method is that the position of the reflecting spot (intracavity pulse focus spot) of the laser beam changes on the SESAM surface, while the incident angle and the reflection angle of the beam remain unchanged. There is an existing method to directly move the SESAM with the direction of the intracavity laser beam normal to the SESAM surface (shown in Fig. 1(a)). However, the rotation error $\Delta\theta$ resulting from the moving of the SESAM affects the path of the oscillation beam and can lead to lock losing of the passively mode-locked laser. In the worst case, the oscillator cannot output a mode-locked laser pulse. Hence we will employ another method.

A rectangular prism is inserted into the mode-locked laser cavity, as shown in Fig. 1(b). According to the characteristic of the rectangular prism, moving the rectangular prism in the principal cross section can adjust the relative position between the intracavity laser beam and the SESAM, making the focal spot of the beam on the SESAM surface move to new position (point 2) without changing the relative position of the incident and the reflection beams. The rotation error $\Delta\theta$ resulting from the moving of the rectangular prism will not affect the path of the oscillation beam, so the laser cavity will maintain a steady CW mode-locked condition and output the mode-locked laser pulse. The method can be used in an LD end-pumped Nd:YVO_4 mode-locked solid-state laser with an SESAM. The experimental setup is shown in Fig. 2.

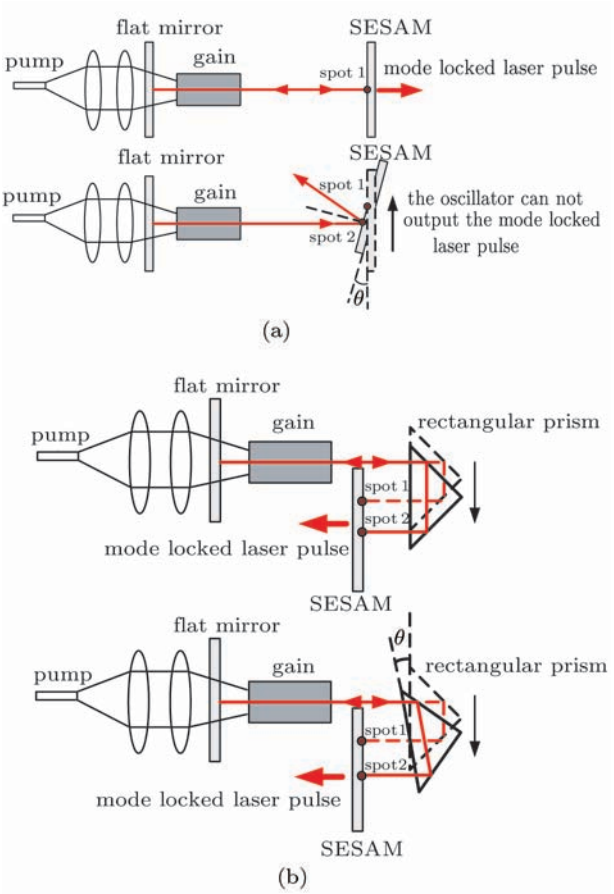


Fig. 1. (colour online) Model of an LD end-pumped mode-locked solid state laser with an SESAM, showing (a) the continuous motion of the SESAM, and (b) the continuous motion of the rectangular prism.

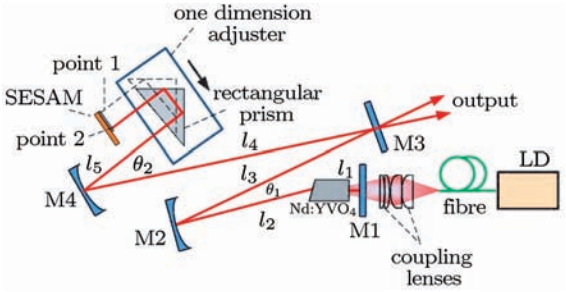


Fig. 2. (colour online) Motion trace of the rectangular prism in the experimental setup.

A high-brightness fibre-coupled laser diode (manufactured by NUFERN) provides an output pump power of up to 20 W at 808 nm. The fibre has a core diameter of 400 μm and a numerical aperture (NA) of 0.22. The temperature of the laser diode is controlled by a temperature control unit to obtain the

best absorption. The pump laser at 808 nm is focused into the crystal by using a 4-lens coupling system. The a-cut Nd:YVO_4 used in our experiment has a Nd^{3+}-doping concentration of 0.3 at.%. The crystal is 3 mm×3 mm×9 mm and wedged. The left side of the Nd:YVO_4 is coated with an anti-reflection film at 1064 nm and the other side is antireflectively (AR) coated at 808 nm and 1064 nm. To reduce the thermal load, the crystal is wrapped with an indium foil and packed inside a copper holder. The laser diode and the crystal are cooled by 15 °C circulating water. The M1 is a flat mirror AR coated at 808 nm and high reflectively (HR) coated at 1064 nm, while M3 is also a flat mirror and is used as the output coupler with $T = 10\%$ at 1064 nm. M2 and M4 are concave mirrors HR coated at 1064 nm with curvature radii of $R_1 = 500$ mm and $R_2 = 208$ mm, respectively. The θ_1 and θ_2 are the incident angles between the incident and the reflected beams on M2 and M4, respectively. The laser crystal Nd:YVO_4 is placed very close to the end mirror, M1, to enhance spatial hole burning (SHB) and to shorten the pulse width.[9] To achieve a stable CW mode-locking operation, we design the total cavity to be 1708 mm long ($l_1 + l_2 = 265$ mm, $l_3 = 839$ mm, $l_4 = 488$ mm and $l_5 = 116$ mm). An SESAM made by Batop Gmbh in Germany is used as the end mirror of the cavity and is simply mounted on a small copper heat sink without active cooling. The absorption ratio and the modulation depth of the SESAM are 2% and 1.2%, respectively.

The dimensions of the prism that is inserted into the mode-locked laser cavity are 20 mm×20 mm×20 mm (shown in Fig. 3). Sides a and b are HR coated at 1064 nm, side c is AR-coated at 1064 nm. The bottom of the prism is fastened to a one-dimensional adjuster, which can be driven manually or by a motor to realize the translation of the rectangular prism in its principal cross-section plane. The oscillator beam that comes from concave mirror M4 is reflected by right-angle surfaces a and b of the prism and is incident on the SESAM with a mode area of spot 1. Through an adjustment of the beam path, the oscillator can be made to operate at the stable CW mode-locked condition. We can make the SESAM and the direction of the beam to be fixed to each other, ensuring that the incident and the reflection angles remain unchanged, and then change the position of the laser beam to move the position of the reflecting point on the SESAM.

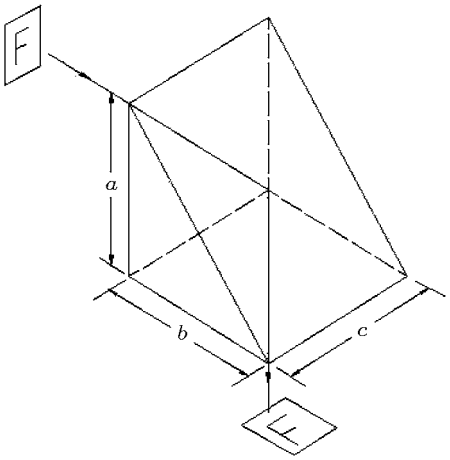


Fig. 3. Scheme of rectangular prism used in the experimental setup.

3. Results and analysis

The mode sizes in the crystal and on the SESAM can be adjusted by using a telescope optical system consisting of concave mirrors in the cavity, and can be individually controlled by M2 and M4. The saturation fluences of the SESAM and the gain medium are $F_{\mathrm{sat,a}} = 70$ μJ/cm^2 and $F_{\mathrm{sat,g}} = 0.12$ J/cm^2, respectively. At a pump power of 7 W, a stable CW mode-locked operation is achieved with 42 μm mode radius on the SESAM (point 1), 154 μm mode radius within the laser crystal and an output coupling of 20%. In stable CW mode-locked operation, we achieve an average power of 3.6 W at a pump power of 10W, corresponding to an optical-optical efficiency of 36%, as shown in Fig. 4. The repetition rate of the impulse sequence is measured to be 86 MHz by using a digital oscilloscope and the spectrum width of the output beam is 0.16 nm, corresponding to the bandwidth of $\Delta v = 37.1$ GHz. The pulse width is measured using an autocorrelator made by the APE

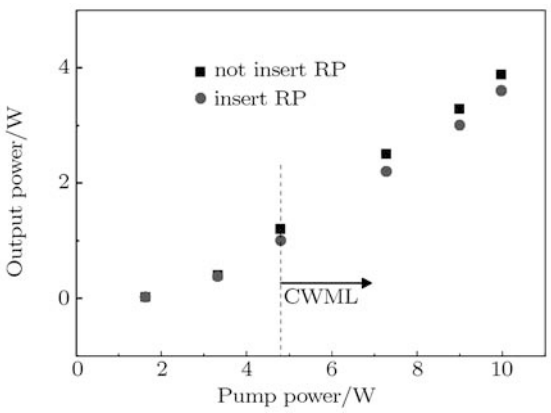


Fig. 4. Output power in passively mode-locked laser.

Company (Germany). The profile of an autocorrelation signal with a full width at half maximum (FWHM) of 22.7 ps in a range of 150 ps is shown in Fig. 5. Taking a hyperbolic secant (sech2), we estimate the pulse duration to be $\Delta\tau = 22.7$ ps$/1.543 = 14.7$ ps. The time-bandwidth product is $\Delta\tau\Delta v = 0.55$.

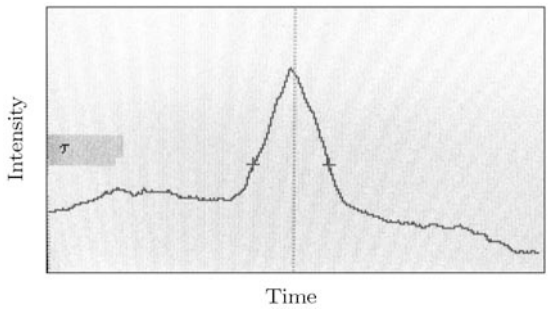


Fig. 5. Measured autocorrelation trace.

After two hours, stable mode locking is captured, we move the rectangular prism in the principal cross section by just 50 μm. Then the mode area (point 1) on the SESAM is adjusted to new focal point 2, which is 50 μm away from point 1. Under the new condition, the cavity also generates stable CW mode-locked pulse sequences (shown in Fig. 6) . The one way output power and the pulse width slightly change to 1.81 W and 15.8 ps, respectively. Table 1 shows the variations of one-way output power P and pulse width τ at different distances from focal point 1 on the SESAM at time intervals of 15 min during a one-hour measurement. The average one-way output laser power is 1.79 W, the average pulse width is 14.8 ps. Output laser power fluctuation $\Delta\bar{P}$ and pulse width fluctuation $\Delta\bar{\tau}$ are 0.032 W and 0.662 ps, respectively. It can be found that the instability $\Delta\bar{P}/P$ of the output power and the instability $\Delta\bar{\tau}/\tau$ of the pulse width are 1.78% and 4.5%, respectively, when the rectangular prism is moved for adjusting the mode area position on the SESAM under the stable CW mode-locked condition.

In summary, by using the simple and practicable method of moving a rectangular prism, we can change the position of a focal spot on an SESAM to avoid the long-time irradiation of a laser on the same position, which solves a series of problems caused by damage to the reflecting elements, such as the SESAM, and prolongs the usage life of the SESAM greatly. The method of moving the rectangular prism to change the position of the oscillation beam can avoid the rotation error caused by the adjustment of the SESAM inside the laser cavity and can ensure the steady operation of the laser when the relative position between the oscillation laser beam and the SESAM is changed.

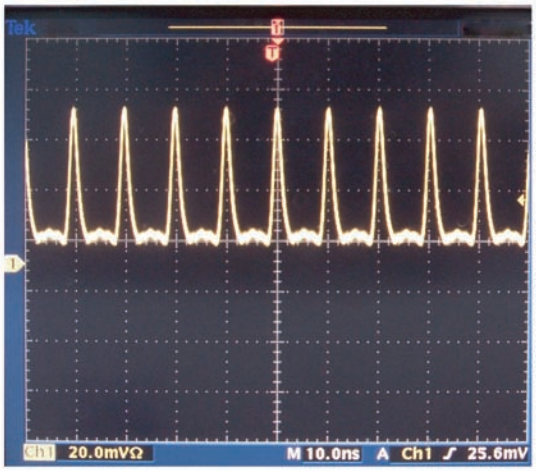


Fig. 6. (colour online) Stable CW mode-locked pulse sequence.

Table 1. One-way output power and pulse widths at different distances from focal point 1.

Time/min	0	15	30	45	60
Distance/μm	0	50	100	150	200
P/W	1.81	1.81	1.80	1.78	1.75
τ/ps	14.7	15.8	13.8	15.1	14.5

4. Conclusion

We demonstrate an LD end-pumped passively mode-locked Nd:YVO_4 solid-state laser with an SESAM, in which the intracavity laser beam spot on the SESAM can be adjusted periodically without breaking the stable CW mode-locked condition in the laser cavity. Inserting a rectangular prism into the laser cavity is a promising approach towards the goal of avoiding the long-time irradiation of the laser beam on the same position of the SESAM, which solves a series of problems caused by damage to the SESAM and greatly prolongs its usage life. The oscillator can generate a stable picosecond pulse sequence at 1064 nm with an output power of 3.6 W, a repetition rate of 86 MHz and a pulse width of 14 ps. Adjusting the laser beam spot on the SESAM by moving the RP, the instabilities of the output power and the pulse width are 1.77% and 4.5%, respectively.

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