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Diode-Pumped Self-Starting Mode-Locked Nd:YVO$_4$ Laser with Semiconductor Saturable Absorber Output Coupler *

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By using a semiconductor saturable-absorber output coupler as a mode-locking device, we experimentally realized the operation of a diode-pumped passively mode-locked Nd:YVO$_4$ laser. Stable laser pulses with duration of 2.3 ps were generated at the output power of about 1W. With increasing the pump power to 9 W, the maximum mode-locked power of 1.7 W was obtained, which corresponds to a slope conversion efficiency of 44% and optical-to-optical conversion efficiency of 19%.

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There is considerable interest in diode-pumped passively mode-locked lasers because of their compactness, robustness and high stability.[1,2] One of the targeted applications is material processing and pulsed laser deposition,[3,4] multiphoton microscopy,[5] and another significant area of applications is optical coherence tomography.[6] In recent years, with the invention and development of the Fabry–Perot saturable absorber[7] and saturable Bragg reflectors (SBRs)[8,9] as well as semiconductor saturable absorber mirrors (SESAM),[10] it is possible for us to produce high average power picosecond laser pulses with self-starting mode-locked technology. Up to now, self-starting mode-locking operation has been demonstrated in many diode-pumped lasers with SESAM;[11−12] picosecond laser pulses at the average output power of more than 10 W were obtained.[13,14] However, the damage threshold of the SESAM limits the further increase of output power because of the focused power intensity. By replacing the SESAM with a semiconductor saturable absorber output coupler (SESAOC), the self-starting diode-pumped mode-locked laser not only will have a potential to generate much higher power, but also can significantly simplify the laser configuration, which has attracted much attention in the design of compact microchip lasers. In 2001, Spühler *et al.* demonstrated a passive Q-switched Nd:YVO$_4$ microchip laser with the SESAOC,[15] with the 160-mW pump power from a diode laser, they obtained 7.7-mW average mode-locking power with the pulse width of 143 ps and the repetition rate of 160 kHz. Recently, a 10-ps mode-locked Nd:YAG laser with the SESAOC was reported by Wang and Ma;[16] the optical-to-optical conversion efficiency is about 6%.

There are many wide advantages of all-solid-state mode-locked lasers modulated by SESAOCs, and it is a competitive research goal to pursue further the higher mode-locking power and shorter pulse width. In this Letter, we report a diode-pumped passively mode-locked Nd:YVO$_4$ laser with the SESAOC, and stable mode-locking pulse with average power 1.7 W of 1064 nm was demonstrated under the pump power 9 W. Pulse width as short as 2.3 ps of infrared laser was also measured at 1 W output power. To our best knowledge, up to now, this is the shortest pulse width from a self-starting mode-locked Nd:YVO$_4$ laser. The slope conversion efficiency corresponding to the maximum output power is 44% and the optical-to-optical conversion efficiency is 19%.

Figure 1 schematically shows the experimental setup. The pump source (Apollo Instruments, Inc.) is a fibre-coupled diode laser with core diameter of 0.6 mm and numerical aperture of 0.22. An optical coupled system is used to focus the pump beam into the gain medium. 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 20°C. The gain medium is α-cut Nd:YVO$_4$ crystal with 1.5 at.% neodymium doping and the dimensions are 4×4 mm in surface aperture and 12 mm in length. The absorption coefficient at 808 nm and at 20°C is 81%. To alleviate the thermal load, the crystal is wrapped by indium foil and packed inside a copper holder, which is cooled by flowing water. The end mirror (M$_1$) is coated with antireflection ($> 98\%$) for the 808-nm pump wavelength and high reflection ($> 99.8\%$) for the 1064-nm lasing radiation. The folding mirror M$_2$, with curvature ra-

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dius of 50 mm, is used to focus the laser beam on the SESAOC, and the spot size is calculated to be about 50 μm in diameter.

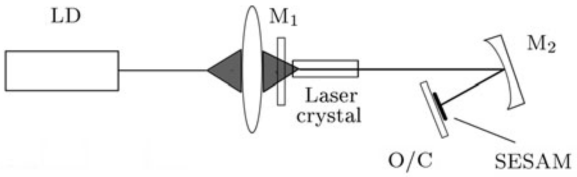

Fig. 1. Layout of the all-solid-state mode-locked Nd:YAO$_4$ laser with SESAOC as both the self-starting mechanics and the output coupler. M_1: plate mirror with dichroic coating; M_2: folding mirror with ROC of 50 mm.

The absorption layer of SESAOC (LT-In$_{0.25}$Ga$_{0.75}$As) was grown by metal organic chemical vapour epitaxy at a substrate temperature of 550°C, a 10-nm-thick GaAs barrier layer was grown at normal temperature (720°C) between the LT-In$_{0.25}$Ga$_{0.75}$As and GaAs buffer layer which grew on a GaAs substrate to improve the quality of the surface of the GaAs substrate. There is another 10-nm-thick GaAs barrier layer on the top of the LT-In$_{0.25}$Ga$_{0.75}$As layer, which acts as the protection layer from the LT-In$_{0.25}$Ga$_{0.75}$As layer to the air.

When the thickness of In$_{0.25}$Ga$_{0.75}$As is larger than the critical thickness, the large lattice mismatch of In$_{0.25}$Ga$_{0.75}$As on GaAs can cause degradations such as surface striations, which can lead to too much non-saturable loss. Therefore, we choose the In$_{0.25}$Ga$_{0.75}$As /GaAs quantum well (QW) structure rather than bulk In$_{0.25}$Ga$_{0.75}$As. The InGaAs/GaAs QW bandgap is not a very critical parameter; it is adjusted approximately to the lasing wavelength.

In order to make In$_{0.25}$Ga$_{0.75}$As as an output coupler, one side of the absorber was coated with anti-reflection coating and the other side deposited with high reflection coating. The anti-reflection film is the hybrid of ZrO$_2$ and Y$_2$O$_3$(4:1) with a total thickness of 1/4 wavelength. The high reflection film is composed of Al$_2$O$_3$/Si/SiO$_2$/Si multiple layers to obtain reflectivity as high as 90%. The absorber is In$_{0.25}$Ga$_{0.75}$As with thickness of 10 nm and grown at a lower temperature (550°C). In this experiment, the SESAOC has a saturated $T_{\rm out}$ of 10% at 1064 nm, it is held on a copper heat sink to reduce the thermal influence.

A nonlinear crystal KTP is inserted in the laser cavity to convert the fundamental wave into the second harmonic (SH) wave for easily observing and monitoring the mode-locked phenomenon. The SH laser after passing through the SESAOC is reflected into a fast photodiode (response time is about 1 ns) and then couples to a digital oscilloscope (Tektronix 520D) with the sampling rate of 2 GHz/s. In general, the oscilloscope displays the modulation traces if the laser runs in a continuous wave mode. With careful alignment to optimize the laser running, we realized stable mode-locking operation and the oscilloscope displays a uniform pulse train. Figure 2 shows the typical mode-locking trace; it reveals a high repetition rate of 1.2 GHz, which is triple the theoretic value depending on the cavity length. The reason for this surprising observed phenomenon is ascribed to the polarization change of the resonate eigenmodes in the cavity, which result from the anisotropies of the gain medium and the nonlinear crystal.[17,18]

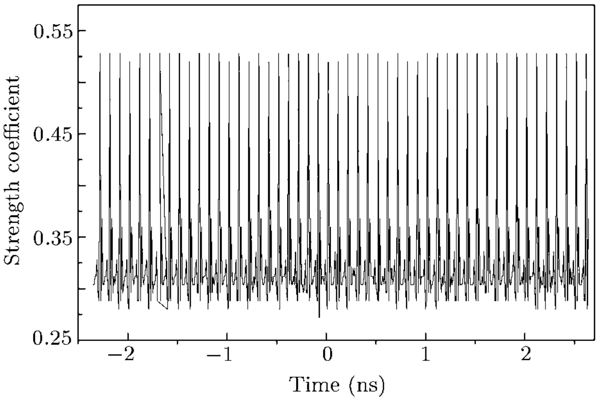

Fig. 2. Continuous wave mode-locking trace.

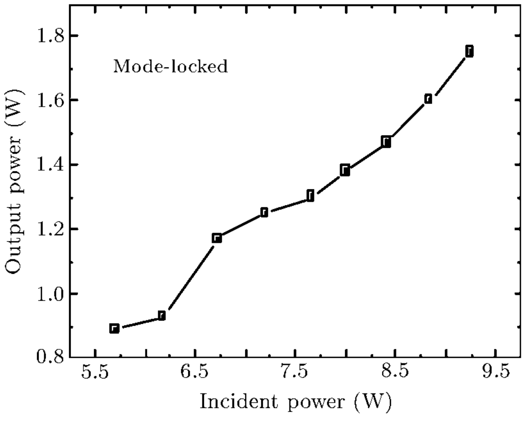

Fig. 3. Output versus incident power.

The dependence of average output power at 1.064 μm with incident pump power in the mode-locked regime is shown in Fig. 3. Under the pump power of 9.25 W, we obtained 1.75 W average mode-locking power at 1064 nm from the laser, corresponding to the slope conversion efficiency of 44% and optic–optic conversion efficiency 19%. The damage threshold of SESAM limits the further increase of stable average output power, and we think that higher mode-locking output should be possible by setting the fold mirror M$_2$ with a longer radius of curvature to enlarge the focused spot on the SESAOC. As a contrast to higher pump power, we also studied the characteristics of mode-locking in the lower pump and noticed that the stability of mode-locking becomes worse when running the laser around the threshold power of 655 mW. In the wide pump range from threshold power to 9 W, the mode locking operation is performed well.

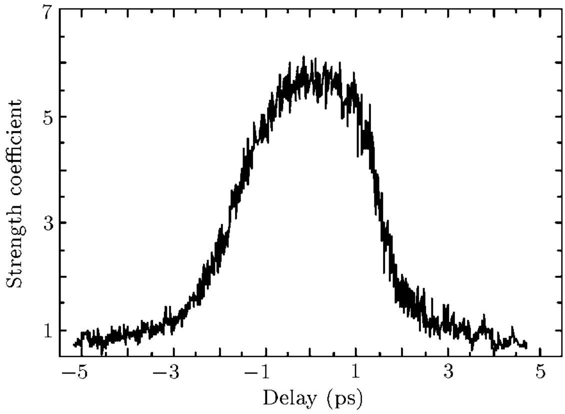

Fig. 4. The autocorrelation trace.

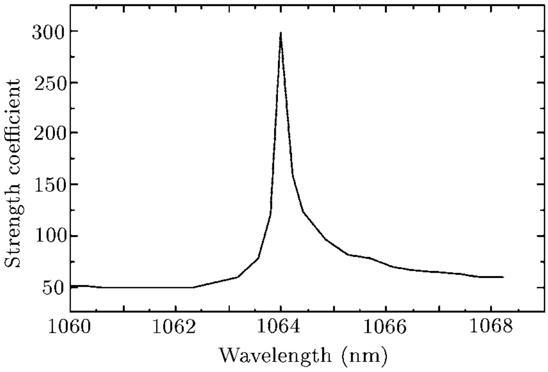

Fig. 5. The mode-locking infrared laser spectrum with the bandwidth about 0.7 nm.

A homemade non-collinear autocorrelator is used to measure the pulse duration. Setting the output power at 1 W, we recorded the autocorrelation trace as shown in Fig. 4, the FWHM width is 3.2 ps of the fundamental wave, corresponding to pulsewidth 2.3 ps with an assumption of the Gaussian pulse shape. Figure 5 shows the mode-locking infrared laser spectrum, the bandwidth is about 0.7 nm. We calculated that the time–bandwidth is about 0.43, which is slightly greater than the theoretical transform limit 0.35.

In conclusion, by using the three-mirror-fold-cavity design, we have realized the stable running of the laser-diode pumped passively mode-locked Nd:YVO_4 laser with a novel SESAOC. The infrared pulse duration of 2.3 ps and bandwidth of 0.7 nm are measured, corresponding to a time–bandwidth product of 0.43. To our knowledge, this is the shortest pulse duration obtained from the SESAOC mode-locking laser technology. A maximum output power as high as 1.7 W is also demonstrated by increasing the pump laser to 9 W. The result with picosecond pulse duration, watt average power and GHz repetition rate will supply a feasible ultrashort laser resource for many applications.

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