

Semiconductor saturable-absorber mirror passively Q -switched Yb:YAG microchip laser

Xia Yin (尹霞), Junqing Meng (孟俊清)*, Jifeng Zu (祖继峰), and Weibiao Chen (陈卫标)

Key Laboratory of Space Laser Communication and Testing Technology, Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, Shanghai 201800, China

*Corresponding author: jqmeng@siom.ac.cn

Received March 6, 2013; accepted May 13, 2013; posted online August 2, 2013

A compact passively Q -switched Yb:YAG microchip laser is demonstrated. Featuring a semiconductor saturable-absorber mirror (SESAM), the laser yields pulses of 219 ps when the length of the microchip Yb:YAG crystal is 100 μm and the beam quality is $M^2 < 1.3$. To the best of our knowledge, pulses from the proposed laser are the shortest Q -switching pulses obtained from Yb:YAG microchip lasers currently available.

OCIS codes: 140.0140, 140.3538, 140.3070, 140.3480.

doi: 10.3788/COL201311.081402.

Laser sources that can produce tens of picoseconds of pulses are desirable for applications such as micromachining, laser ranging, nonlinear studies, medical surgery, optical communications, and pollution monitoring^[1]. Motivated by the compactness and simplicity of the passively Q -switched microchip laser, significant research efforts have been directed toward shorter pulses and higher pulse energies. In 1993, the concept of the microchip laser was first proposed^[2]. To date, many works on passively Q -switched microchip lasers with Nd-doped crystals as gain media have been reported. Nd:YAG passively Q -switched with Cr^{4+} :YAG saturable absorbers can generate pulses with pulse widths of 337^[3] and 218^[4] ps. Nd:LSB Q -switched with a semiconductor antiresonant Fabry-Perot saturable absorber (A-FPSA) systems could also generate pulses of 180 ps^[5]. Compared with bulk crystal saturable absorbers, semiconductor saturable-absorber mirrors (SESAMs) allow shorter cavity lengths and, therefore, shorter pulse widths. Nd:YVO₄ with SESAM could achieve pulses of 56^[6] and 37^[7] ps; very recently, pulses as short as 22 ps were reported^[8]. However, the pulse energy obtained from Nd:YVO₄ microchips as gain media is usually about 100 nJ or lower. Compared with Nd:YVO₄, Yb:YAG has a longer fluorescence lifetime (951 μs) for energy storage, lower quantum defect (8.6%), broader absorption bands (10 nm at around 940 nm), higher doping concentrations that correspond to shorter absorption lengths, relatively low laser cross-sections for obtaining high pulse energies, and excellent thermal properties^[2,9–12]. In addition, laser wavelengths of about 1030 nm overlap with the peak emission spectrum of Yb fiber lasers, which signifies more gain with fiber amplification. With Cr^{4+} :YAG as a passive Q -switch, Yb:YAG microchip lasers generate pulses of 480 ps and pulse energy as high as 13 μJ ^[1]. By applying diamond windows as surface heat spreaders, a pulse train with a pulse energy of 287 μJ and pulse width of 650 ps may be obtained^[13].

In 2001, Spühler *et al.*^[14] presented a passively Q -switched Yb:YAG microchip laser with a pulse duration of 530 ps. This laser featured the following components: a pump diode at 968-nm wavelength, a SESAM with

1.6% modulation depth, and a 200- μm long Yb:YAG microchip as the gain medium. To achieve shorter pulses, we adopt a SESAM with a deeper modulated depth and a Yb:YAG microchip crystal with a shorter length. Yb:YAG has a quasi-three-level system that can achieve high laser thresholds. Furthermore, the deeper the modulation depth, the more difficult it becomes to achieve high laser outputs. Thus, instead of 968 nm, our pump diode is pumped at 940 nm because of its reduced absorption length and wider absorption band^[14]. In this letter, by carefully calculating the laser threshold, we can obtain pulses as short as 219 ps with a SESAM of 5% modulation depth.

Passively Q -switched microchip lasers with SESAMs are very simple and compact. Figure 1 shows a schematic of the experimental setup, which consists of a Yb:YAG microchip crystal sandwiched between a SESAM and a 3% output coupler, a dichroic beam splitter, and a coupling lens pair. The laser crystal was pumped by a fiber-coupled laser-diode (LD) with a core size of 105 μm and numerical aperture (NA) of 0.15. The length of the Yb:YAG crystal was 100 μm and had a doping concentration of 20%. One side of the gain medium was coated with an anti-reflecting (AR) film ($R < 0.01$) at both 940 and 1030 nm; the other side was coated with an AR film ($R < 0.01$) at 1030 nm and a highly reflecting (HR) film ($R > 0.99$) at 940 nm to increase the absorption of the pump power through a round-trip pass instead of a single pass and reduce the heat load of the SESAM. The SESAM used was obtained from BATOP Inc. and had

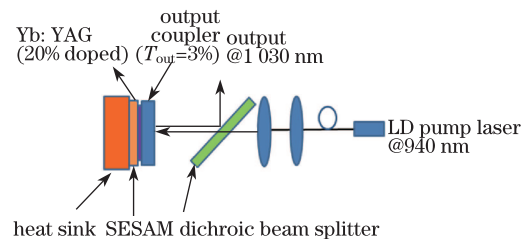


Fig. 1. (Color online) Schematic diagram for the laser-diode end-pumped SESAM passively Q -switched Yb:YAG microchip laser.

a modulation depth of 4%, relaxation time constant of 27 ps, and saturation fluence of $118 \mu\text{J}/\text{cm}^2$ at 1064 nm ^[15]. For the laser wavelength of 1030 nm , the modulation depth was about 5%; the two other lasers remained almost unchanged. To achieve better thermal contact, the components were pressed tightly until the interference fringes between them disappeared. The dichroic beam splitter transmitted the pump light and reflected the output beam in the 45° direction; thus, a laser beam can be obtained in the vertical direction of the pump beam. Coupling optics was used to image the pump beam on the gain medium and produce a pump light footprint of about $105 \mu\text{m}$ on the crystal. It consisted of a collimating lens and a focusing lens with identical focal lengths of 18.4 mm . The center wavelength of the pump light was 941.3 nm and had a spectrum width of 2.5-nm full-width at half-maximum (FWHM). *Q*-switched pulses were received by a Si photodiode with a bandwidth of 7.5 GHz and recorded by a Tektronix digital oscilloscope with 12-GHz bandwidth. The output laser beam quality was analyzed using a Spiricon M²-200S laser beam analyzer, and the pulse spectrum was monitored using a Yokogawa optical spectrum analyzer.

To determine the absorption efficiency of pumping light, the pump light is incident on the gain medium at an angle of 45° relative to the optical axis. The incident pump power obtained after passing through the coupling optics and the residual power in the reflected direction were then measured. The coated Yb: YAG diode is anti-reflective and highly reflective of the pump light in the 0° direction. Because the incident pump is oriented toward the 45° direction, reflection and transmission losses of 10% and $2.5\times$ the optical length, respectively, were considered in the computations. The measured effective absorption efficiency in the 0° direction is thus determined to be 19%. For example, when the incident pump power is 931 mW ,

the absorbed pump power is about 180 mW . The average output power as a function of the absorbed pump power as well as the output beam profile are shown in Fig. 2. As seen in Fig. 2(a), the lasing threshold is about 90 mW , and the average output power increases linearly with the pump power. The slope efficiency is about 12.5%. With an absorbed pump power and average output power of 150 and 7 mW , respectively, the transverse output beam profile was measured and results are shown in Fig. 2(b); a near-fundamental transverse electromagnetic mode (TEM₀₀) may be observed. Figure 2(c) shows the measured output laser beam quality with $M_x^2=1.292$ and $M_y^2=1.128$. While the laser operates with a very short cavity of around $100 \mu\text{m}$, it oscillates in a single longitudinal mode at 1030.9 nm . The number of modes can be calculated using^[7]

$$m = \frac{\Delta\nu_g}{\left(\frac{c}{2nl_g}\right)}, \quad (1)$$

where $\Delta\nu_g=1.31\times 10^{12} \text{ Hz}$ is the FWHM gain bandwidth and $n=1.84$ is the refractive index of the gain media. Through calculation, $m = 1.6 < 2$ is obtained. The pulse spectrum is shown in Fig. 2(d). The center wavelength is 1030.9 nm and the spectrum width is 0.15 nm .

The repetition rate was measured as a function of the absorbed pump power. Figure 3 shows the nearly linear plot of repetition rate versus absorbed pump power.

The repetition rate can be obtained using^[7]

$$f_{\text{rep}} \approx \frac{g_0 - (l_{\text{out}} + A_0)}{2\Delta R\tau_L}, \quad (2)$$

where g_0 is the small-signal gain coefficient, l_{out} is the output coupling coefficient defined by $T_{\text{out}} = 1 - \exp(-l_{\text{out}})$, T_{out} is the transmission of the output coupler, A_0 is the absorbance of the SESAM at low pulse fluence, and τ_L is the upper-state lifetime of the gain medium. Since the small-signal gain coefficient g_0 is a linear function of the pump power, the pulse repetition rate f_{rep} is proportional to the pump power. As shown in Fig. 3(a), the repetition rate increases approximately linearly with increasing pump power. Therefore, this tendency of increment fits the theory.

With the SESAM as the *Q*-switch, the pulse width is given by^[7]

$$\tau_p \approx \frac{3.52T_R}{\Delta R}, \quad (3)$$

where T_R is the cavity round-trip time and related to the length of the gain medium given by $T_R=2L_g/v_g$, L_g is the length of the gain medium, and v_g is the speed of light in the gain medium. When the length of the microchip Yb: YAG crystal is $100 \mu\text{m}$, 87-ps pulses may be expected by taking into account the modulation depth of the SESAM, which is 5%. However, pulses of 219 ps are measured. These longer pulses may be explained by the etalon effect of the air gap between the gain plate and the SESAM. Moreover, the modulation depth of the SESAM is related to the pulse fluence in the cavity^[15] and shallower at low absorbed pump power than at high absorbed pump power.

Figure 3(c) shows the oscilloscope trace of the pulse

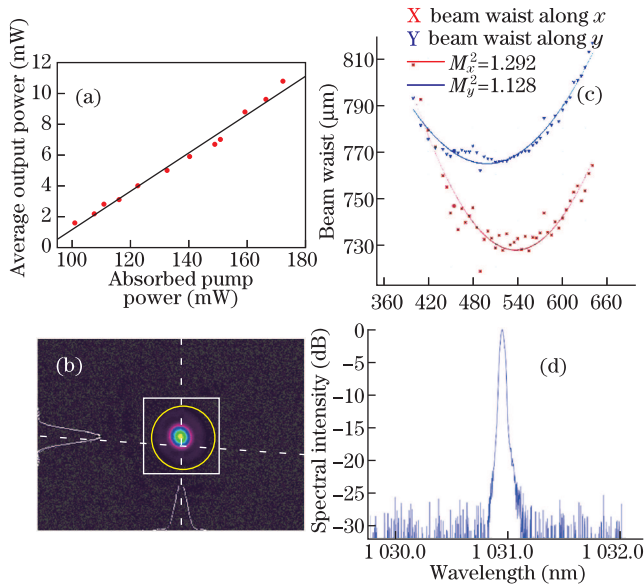


Fig. 2. (Color online) (a) Average output power as a function of the incident pump power of the SESAM passively *Q*-switched Yb:YAG microchip laser in a gain medium with a length of $100 \mu\text{m}$. (b) Output beam and transverse beam profiles. (c) Measured beam quality factors. (d) Pulse spectrum.

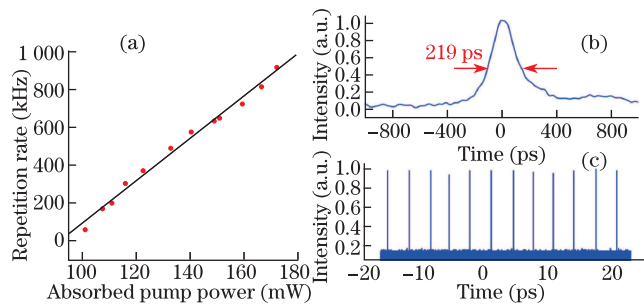


Fig. 3. (Color online) (a) Pulse repetition rate as a function of the incident pump power of the passively Q -switched Yb:YAG microchip laser for the gain medium with a length of 100 μm . (b) Passively Q -switched microchip laser pulses with a 219-ps pulse duration (FWHM). (c) Oscilloscope trace of the laser pulse trains with a repetition rate of 288 kHz when the incident pump power is 700 mW.

trains with a 288-kHz pulse repetition rate when the average output power is 3 mW. The fluctuation of the output pulse amplitudes is less than 6%, indicating a respectively stable passively Q -switched laser operation.

For Yb:YAG pumping at 940 nm, the energy difference between the lower laser and ground levels is small, which leads to significant thermal population of the lower laser level. Some amount of pump power density is necessary just to reach transparency at the laser wavelength, making it necessary to pump the material with a sufficiently high pump power density to reach the threshold without significantly increasing the temperature of the crystal^[16]. For our lasers, the use of multiple pump beams to pass through the crystal may be expected to enhance the efficiency. Thus, by employing a SESAM with a deeper modulation depth, shorter pulses could be obtained. The performance of the laser can also be improved by monolithically bonding the gain medium with the SESAM^[17] or by operating the laser at low temperature^[18,19].

In conclusion, the operation of a passively Q -switched LD-pumped Yb:YAG microchip laser using SESAM is demonstrated. With a 3% output coupler and SESAM modulation depth of 5%, relatively stable pulses are obtained when the length of the microchip Yb:YAG crystal is 100 μm . Pulse widths of 219 ps and laser beam qualities of $M_x^2=1.292$ and $M_y^2=1.128$ are achieved. Pulses achieved by the proposed system are currently the shortest Q -switching pulses obtained from Yb:YAG microchip lasers. The performance of the SESAM passively Q -

switched Yb:YAG microchip laser can be further improved by monolithically bonding the gain medium with the SESAM and using the multi-pass pumping method.

References

1. J. Dong, A. Shirakawa, and K. I. Ueda, *Appl. Phys. B: Lasers Opt.* **85**, 513 (2006).
2. A. Giesen, H. Hügel, A. Voss, K. Witting, U. Brauch, and H. Opower, *Appl. Phys. B: Lasers Opt.* **58**, 365 (1994).
3. J. J. Zayhowski and C. Dill III, *Opt. Lett.* **19**, 1427 (1994).
4. J. J. Zayhowski, *J. Alloy Compd.* **303**, 393 (2000).
5. B. Braun, F. X. Kärtner, U. Keller, J. P. Meyn, and G. Huber, in *Proceedings of Advanced Solid State Lasers Q1* (1996).
6. B. Braun, F. X. Kärtner, G. Zhang, M. Moser, and U. Keller, *Opt. Lett.* **22**, 381 (1997).
7. G. J. Spühler, R. Paschotta, R. Fluck, M. Braun, G. Zhang, E. Gini, and U. Keller, *J. Opt. Soc. Am. B* **16**, 376 (1999).
8. A. C. Butler, D. J. Spence, and D. W. Coutts, *Appl. Phys. B: Lasers Opt.* **109**, 1 (2012).
9. J. Dong, M. Bass, Y. Mao, P. Z. Deng, and F. X. Gan, *J. Opt. Soc. Am. B* **20**, 1975 (2003).
10. M. Tsunekane and T. Taira, *Opt. Lett.* **31**, 2003 (2006).
11. J. Dong, G. Z. Xu, J. Ma, M. J. Cao, Y. Cheng, K. Ueda, H. Yagi, and A. A. Kaminskii, *Opt. Mater.* **34**, 959 (2012).
12. H. Wu, P. Yan, and Q. Liu, *Chin. Opt. Lett.* **1**, 697 (2003).
13. W. Z. Zhuang, Y. F. Chen, K. W. Su, K. F. Huang, and Y. F. Chen, *Opt. Express* **20**, 22602 (2012).
14. G. J. Spühler, R. Paschotta, M. P. Kullberg, M. Graf, M. Moser, E. Mix, G. Huber, C. Harder, and U. Keller, *Appl. Phys. B: Lasers Opt.* **72**, 285 (2001).
15. <http://www.batop.com>.
16. A. Giesen and J. Speiser, *IEEE J. Quantum Electron.* **13**, 598 (2007).
17. A. Steinmetz, D. Nodop, J. Limpert, R. Hohmuth, W. Richter, and A. Tünnermann, *Appl. Phys. B: Lasers Opt.* **97**, 317 (2009).
18. J. Wang, Z. Zhang, X. Cheng, L. Li, X. Shi, X. Zhu, and W. Chen, *Chin. Opt. Lett.* **9**, 111403 (2011).
19. W. Z. Zhuang, Y. F. Chen, K. W. Su, K. F. Huang, and Y. F. Chen, *Opt. Express* **20**, 22602 (2012).