# Diode-pumped passively mode-locked femtosecond $Yb:(Y_{0.9}La_{0.1})_2O_3$ ceramic laser

**Jiangfeng Zhu (朱江峰)[1], Zhaohua Wang (王兆华) [2*], Qing Wang (王 庆)[2], Zhiguo Zhang (张治国)[2], Qiuhong Yang (杨秋红)[3], Junhong Yang (杨军红)[4], Yunfeng Ma (麻云凤)[4], and Zhiyi Wei (魏志义)[2**]**

[1]*School of Technical Physics, Xidian University, Xi'an 710071, China*

[2]*Beijing National Laboratory for Condensed Matter Physics, Institute of Physics, Chinese Academy of Sciences, Beijing 100190, China*

[3]*School of Materials Science and Engineering, Shanghai University, Shanghai 200072, China*

[4]*Beijing GK Laser Technology Co., Ltd, Beijing 100085, China*

**Corresponding author: zhwang@iphy.ac.cn; **corresponding author: zywei@iphy.ac.cn*

Received May 10, 2012; accepted July 10, 2012; posted online November 30, 2012

We experimentally demonstrate a diode-pumped passively mode-locked femtosecond laser with $Yb^{3+}$-doped yttrium lanthanum oxide ceramic. Mode-locking is achieved by using a semiconductor saturable absorber mirror, and intracavity dispersion is compensated by a pair of SF6 prisms. Laser pulses as short as 357 fs at a central wavelength of 1 075 nm are obtained. The maximum average output power is 670 mW under 4.5 W of pumping power with a slope efficiency of 20%. To the best of our knowledge, this is the shortest pulse generated from Yb-doped yttrium lanthanum oxide ceramic lasers with a sub-500 fs pulse duration.

*OCIS codes:* 140.3480, 140.3615, 140.4050, 140.7090.

*doi: 10.3788/COL201210.121403.*

In the past several years, trivalent ytterbium ion ($Yb^{3+}$)-doped material has attracted considerable attention as a promising ultrafast laser medium. A variety of $Yb^{3+}$-doped crystalline hosts have been developed for laser operation. The highest average output power derived from a mode-locked laser oscillator was achieved from a thin disk laser based on $Yb:Lu_2O_3$ with an average power of 141 W and a pulse duration of 738 fs[1]. Joule-level pulse energy was achieved from a chirped pulse amplification laser system based on a Yb:YAG thin-disk laser with a repetition rate of ~100 Hz[2]. The shortest pulse duration was realized with a passively mode-locked Yb:YCOB laser[3] and a Kerr-lens mode-locked Yb:YAG laser[4], which both generated 35-fs pulses. Such pulse duration is comparable to conventional prism-pair-based femtosecond Ti:sapphire oscillator, making the Yb laser a promising femtosecond laser source with a sub-100 fs pulse duration. Other kinds of Yb-doped crystals have also been successfully realized by either passive mode-locking or Kerr-lens mode-locking; these crystals include vanadates $Yb:YVO_4$[5] and $Yb:LuVO_4$[6], oxyorthosilicates Yb:LYSO[7] and Yb:GYSO[8], double-borate Yb:BOYS[9], fluorite Yb:YLF[10], sesquioxide $Yb:Sc_2O_3$[11], and $Yb:CaGdAlO_4$[12].

Among these materials, the sesquioxides $Re_2O_3$ (Re=Y, Sc, Lu)[13] are highly attractive materials for high-power femtosecond laser because of their excellent thermal conductivity and relatively broad emission spectra compared with those of YAG[14]. However, growing $Re_2O_3$ single crystalline requires a high melting temperature. For example, the melting temperature for $Y_2O_3$ single crystalline is 2 430 °C, and the transition from cubic to hexagonal phase occurs at a temperature of about 2 280 °C. These conditions make fabricating high-quality, large-size crystals extremely difficult. The development of transparent $Y_2O_3$ ceramic enables the fabrication of large homogeneous bulk at a relatively low sintering temperature of 1 700 °C, which is about 700 °C lower than the melting point of $Y_2O_3$ crystal[15]. Watt-level continuous-wave (CW) and mode-locking experiments have exhibited that $Yb:Y_2O_3$ ceramic is a promising diode-pumped laser medium[16−19]. Adding $La_2O_3$ as a sintering aid to form yttrium lanthanum oxide ceramic ($Yb:(Y_{1-x}La_x)_2O_3$) further decreases sintering temperature to 1 450–1 600 °C[20], thereby shortening the fabrication period and reducing the cost of mass production. A CW laser operation for $Yb:(Y_{1-x}La_x)_2O_3$ ($x = 0.1$) ceramic with a low threshold and 52% slope efficiency was reported[21]. Picosecond mode-locking with a 174-ps duration and 162-mW power was demonstrated by Li *et al.*[22], and picosecond mode-locking with a 3.1-ps duration and 1.2-W power was achieved by Zhang *et al.*[23]. Sub-picosecond operation was realized by Wang *et al.*[24], but the pulse duration was 730 fs and the output power was only 92 mW because of the lossy optics applied in the experiment.

In this letter, we report a diode-pumped passively mode-locked femtosecond $Yb:(Y_{0.9}La_{0.1})_2O_3$ ceramic laser that generates 357-fs pulses at 1 075 nm with an average power of 670 mW, a value shorter than that derived in Ref. [24]. We achieve this considerably higher output power by optimizing the experimental setup through a prism pair for chirp compensation.

$Yb:(Y_{0.9}La_{0.1})_2O_3$ ceramic is fabricated with high-purity $Y_2O_3$ (99.99%), $La_2O_3$ (99.95%), and $Yb_2O_3$ (99.99%) powder, sintered at 1 450 to 1 550 °C for 2–10 h. The $Yb^{3+}$ concentration is 5 at-%. The absorption and fluorescence spectra of the $Yb:(Y_{0.9}La_{0.1})_2O_3$ ceramic at room temperature are shown in Fig. 1. The absorption spectra are measured by Fourier-transform infrared spectroscopy, and the fluorescence spectra are calibrated using a monochromator with an excitation light of 940 nm.

 

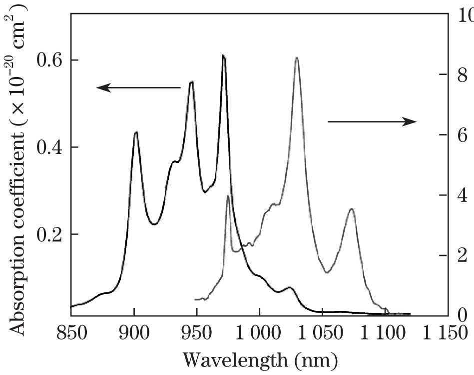


Fig. 1. Absorption and fluorescence spectra of the 5 at.-%-doped Yb:$(Y_{0.9}La_{0.1})_2O_3$ ceramic at room temperature.

The coverage of the broad absorption bandwidth is from 850 to 1 050 nm with peaks at 904, 948, and 974 nm, whose corresponding absorption cross-sections are $0.43\times10^{-20}$, $0.55\times10^{-20}$, and $0.61\times10^{-20}$ cm$^2$, respectively. Each peak has a bandwidth (full-width at half-maximum (FWHM)) of more than 10 nm, which is highly suitable for diode pumping without the need for precise temperature control. The emission spectra with three peaks that correspond to transitions from substate $^2F_{5/2}$ to ground state $^2F_{7/2}$ are located at 976, 1 032, and 1 075 nm. The FWHM bandwidths of each peak at 1 032 and 1 075 nm are 20 and 24 nm, respectively, both supporting the sub-100-fs Fourier transform-limited (TL) pulse duration.

Figure 2 depicts the experimental setup. A 2-mm-thick uncoated Yb:$(Y_{0.9}La_{0.1})_2O_3$ ceramic with a 3×3 (mm) cross-section is used as the gain medium. To eliminate surface reflection loss, the ceramic is placed at Brewster's angle. To eliminate heat, the ceramic is wrapped with an indium film and placed on a water-cooled copper mount at 12 °C. The pump is a fiber-coupled diode laser that emits a maximum power of 7 W at 976 nm (Jenoptik, JOLD-7.5-BAFC-105). The diverging output from the fiber (NA=0.22, 50-$\mu$m core diameter) is re-imaged into the ceramic by two 50-mm focal length achromatic doublet lenses, thereby resulting in a diameter of about 60 $\mu$m. The laser cavity is designed as an astigmatically compensated $X$-type cavity with two arms. Folding mirrors M2 and M3 have a radius of curvature (ROC) of 200 mm. The laser beam is focused onto a semiconductor saturable absorber mirror (SESAM) by a concave mirror (M4) with ROC = 300 mm. This SESAM enables the initiation of self-starting mode-locking. The SESAM (Batop GmbH) is designed to work at approximately 1 040 nm (±40 nm) with a modulation depth of 0.4%, a saturation fluence of 120 $\mu$J/cm$^2$, and a relaxation time of less than 500 fs. Two SF6 prisms with a tip-to-tip distance of ~40 cm are used to introduce a negative group delay dispersion of about −2 000 fs$^2$ for the chirp compensation of the Yb ceramic and SESAM. The output coupler has a transmission rate of 2.4% (1 040±50 nm). The total cavity length is 1.86 m, which corresponds to a repetition frequency of 80.6 MHz.

The laser has a threshold pumping power of 0.74 W. With increasing pumping power, the laser runs at an unstable $Q$-switched mode-locking state. When the pumping power exceeds 1.5 W, it turns to stable CW mode-locking. Figure 3 shows the dependence of output power on incident pumping power. The maximum output power for CW mode-locking is about 670 mW at 4.5-W pumping power. The calculated slope efficiency is 20%. Mode-locking runs very stable by monitoring the pulse train using a fast photodiode and digital oscilloscope, and the long-term power stability is better than 3% in a 2-h period. The output power is limited by multipulse instability with increasing pumping power; at the same time, the beam profile worsens. The broad emission bandwidth at 1 075 nm is favorable for obtaining a short pulse duration even though the emission cross-section at 1 032 nm is larger than that at 1 075 nm (Fig. 1). Given the strong reabsorption effect, laser oscillation is suppressed at 1 032 nm[17]; mode-locking therefore runs at 1 075 nm. Figure 4(a) shows the mode-locking spectra recorded by a high-resolution infrared spectrometer. The FWHM bandwidth is 4.6 nm and the spectrum supports a Fourier TL pulse duration of 284 fs. The pulse duration is monitored by using an intensity autocorrelator (FR-103MN, Femtochrome Research, Inc.). Figure 4(b) depicts the intensity autocorrelation trace of the shortest pulse duration. Assuming a sech$^2$ pulse shape results in a pulse duration of 357 fs. The calculated time-bandwidth product is 0.427, which is bigger than 0.315, the transform limit of sech$^2$ pulse. This result indicates the presence of a residual chirp in the cavity. Further efforts to minimize the residual chirp may obtain shorter pulses close to the TL pulse duration. The current bandwidth of 4.6 nm is considerably narrower than the FWHM

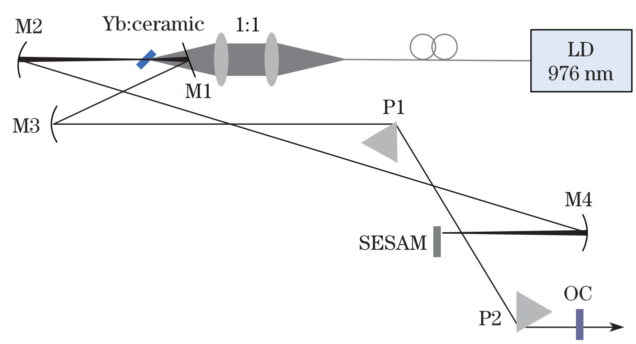


Fig. 2. Experimental setup. M1: plane dichroic mirror with a high transmission at 976 nm and a high reflection at 1 020–1 200 nm; M2 and M3: curved high reflection (HR) mirrors with ROC=200 mm; M4: curved HR mirrors with ROC=300 mm; P1 and P2: SF6 prisms; LD: laser diode; OC: output coupler.

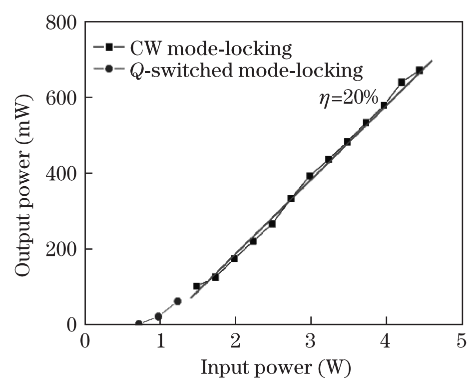


Fig. 3. (Color online) Average output power as a function of input power. The red line indicates a slope efficiency of 20%.

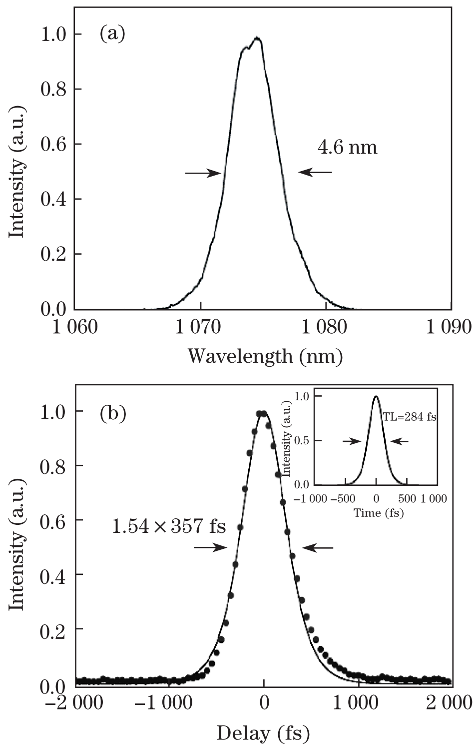


Fig. 4. (a) Spectrum and (b) autocorrelation trace of mode-locked pulses. Dots: measurement data; solid curve: $sech^2$ fitting curve. Inset shows the Fourier TL pulse duration of the spectrum in (a).

emission bandwidth at 1 075 nm. Therefore, a sub-100 fs pulse duration may be obtained by exploring methods for broadening mode-locking spectra.

In conclusion, we demonstrate a diode-pumped femtosecond mode-locked Yb:$(Y_{0.9}La_{0.1})_2O_3$ ceramic laser. With a 5 at-%-doped Yb:$(Y_{0.9}La_{0.1})_2O_3$ ceramic, femtosecond pulses with a 357-fs duration and 670-mW average power at 1 075 nm are achieved. This is the shortest pulse generated from Yb-doped yttrium lanthanum oxide ceramic lasers. The low fabrication temperature and excellent optical performance make Yb:$(Y_{0.9}La_{0.1})_2O_3$ ceramic a promising material for diode-pumped ultrafast laser that can generate compact, high power sub-100 fs pulses in the near-infrared field.

This work was supported by the National Natural Science Foundation of China (Nos. 10874237, 10804128, and 60808007), the National "863" Program of China (No. 2011AA030205), and the Fundamental Research Funds for the Central Universities (No. K50511050001).

## References

1. C. Baer, C. Kränkel, C. Saraceno, O. Heckl, M. Golling, R. Peters, K. Petermann, T. Südmeyer, G. Huber, and U. Keller, Opt. Lett. **35,** 2302 (2010).
2. J. Tümmler, R. Jung, H. Stiel, P. V. Nickles, and W. Sandner, Opt. Lett. **34,** 1378 (2009).
3. A. Yoshida, A. Schmidt, V. Petrov, C. Fiebig, G. Erbert, J. Liu, H. Zhang, J. Wang, and U. Griebner, Opt. Lett. **36,** 4425 (2011).
4. S. Uemura and K. Torizuka, Jpn. J. Appl. Phys. **50,** 010201 (2011).
5. A. A. Lagatsky, A. R. Sarmani, C. T. A. Brown, W. Sibbett, V. E. Kisel, A. G. Selivanov, I. A. Denisov, A. E. Troshin, K. V. Yumashev, N. V. Kuleshov, V. N. Matrosov, T. A. Matrosova, and M. I. Kupchenko, Opt. Lett. **30,** 3234 (2005).
6. S. Rivier, X. Mateos, J. Liu, V. Petrov, U. Griebner, M. Zorn, M. Weyers, H. Zhang, J. Wang, and M. Jiang, Opt. Express **14,** 11668 (2006).
7. W. Li, S. Xu, H. Pan, L. Ding, H. Zeng, W. Lu, C. Guo, G. Zhao, C. Yan, L. Su, and J. Xu, Opt. Express **14,** 6681 (2006).
8. B. Zhou, Z. Wei, Y. Zhang, X. Zhong, H. Teng, L. Zheng, L. Su, and J. Xu, Opt. Lett. **34,** 31 (2009).
9. F. Druon, S. Chénais, P. Raybaut, F. Balembois, P. Georges, R. Gaumé, G. Aka, B. Viana, S. Mohr, and D. Kopf, Opt. Lett. **27,** 197 (2002).
10. N. Coluccelli, G. Galzerano, L. Bonelli, A. Di Lieto, M. Tonelli, and P. Laporta, Opt. Express **16,** 2922 (2008).
11. M. Tokurakawa, A. Shirakawa, K. Ueda, H. Yagi, T. Yanagitani, and A. A. Kaminskii, Opt. Lett. **32,** 3382 (2007).
12. Y. Zaouter, J. Didierjean, F. Balembois, G. Lucas Leclin, F. Druon, P. Georges, J. Petit, P. Goldner, and B. Viana, Opt. Lett. **31,** 119 (2006).
13. K. Petermann, G. Huber, L. Fornasiero, S. Kuch, E. Mix, V. Peters, and S. A. Basun, J. Lumin. **87-89,** 973 (2000).
14. P. Lacovara, H. K. Choi, C. A. Wang, R. L. Aggarwal, and T. Y. Fan, Opt. Lett. **16,** 1089 (1991).
15. N. Saito, S. Matsuda, and T. Ikegami, J. Am. Ceram. Soc. **81,** 2023 (1998).
16. K. Takaichi, H. Yagi, J. Lu, J. Bisson, A. Shirakawa, and K. Ueda, Appl. Phys. Lett. **84,** 317 (2004).
17. J. Kong, D. Y. Tang, J. Lu, K. Ueda, H. Yagi, and T. Yanagitani, Opt. Lett. **29,** 1212 (2004).
18. G. Q. Xie, D. Y. Tang, L. M. Zhao, L. J. Qian, and K. Ueda, Opt. Lett. **32,** 2741 (2007).
19. M. Tokurakawa, K. Takaichi, A. Shirakawa, K. Ueda, H. Yagi, T. Yanagitani, and A. A. Kaminskii, Appl. Phys. Lett. **90,** 071101 (2007).
20. Q. Yang, J. Ding, H. Zhang, and J. Xu, Opt. Commun. **273,** 238 (2007).
21. Q. Hao, W. Li, H. Zeng, Q. Yang, C. Dou, H. Zhou, and W. Lu, Appl. Phys. Lett. **92,** 211106 (2008).
22. W. Li, Q. Hao, Q. Yang, and H. Zeng, Laser Phys. Lett. **6,** 559 (2009).
23. Y. Zhang, Z. Wei, Z. Wang, Z. Zhang, H. Zhang, and Q. Yang, in *Proceedings of Conference on Lasers and Electro-Optics/Pacific Rim 2011* 1844 (2011).
24. Z. Wang, Z. Wei, Q. Wang, D. Li, Z. Zhang, Y. Zhang, Q. Yang, H. Zhang, and S. Lu, Laser Phys. **22,** 129 (2012).