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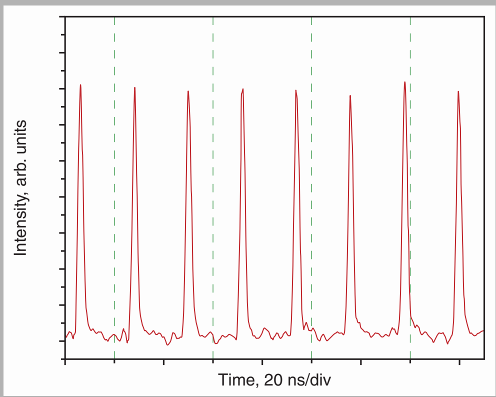
**Abstract:** A diode-pumped picosecond laser was demonstrated with $Yb^{3+}$-doped yttrium lanthanum oxide transparent laser ceramic Yb:$(Y_{1-x}La_x)_2O_3$ ($x = 0.1$), which was fabricated with nanopowders and sintered in $H_2$ atmosphere. Passive mode-locking was realized for the first time to our knowledge with a semiconductor saturable absorber mirror, generating pulses of 174 ps at the central wavelength 1032.5 nm with the average output power 162 mW under a diode-laser pump power of 3.2 W.




The 90.7-MHz repetition rate of the CW mode-locked Yb:$Y_{1.8}La_{0.2}O_3$ ceramic laser pulses



# Diode-pumped passively mode-locked $Yb^{3+}$-doped yttrium lanthanum oxide ceramic laser

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## 1. Introduction

In the past ten years, ytterbium ion has been recognized as a very attractive dopant [1–3] for high-power and ultrashort laser operations directly pumped by high-power high-brightness InGaAs laser diodes. Efficient laser operations have already been demonstrated in many ytterbium-doped materials, such as tungstates Yb:KGW [4], garnet Yb:YAG [5–8], oxyorthosilicates Yb:GSO, and Yb:LYSO [9–11]. Furthermore, ytterbium-doped fibers have been recognized in recent years as very attractive active media for diode-pumped laser oscillators [12–20]. Ytterbium-doped double clad fiber lasers can offer an excellent combination of high power laser output and good spatial beam quality [21–24]. Recently, polycrystalline ceramic laser materials have attracted considerable attention because of their favorable characteristics compared with single crystals, such as easy fabrication, inexpensive, mass producible, high doping concentration and multilayer or multifunctional structure [25,26]. Cubic $Y_2O_3$ crystal is an ideal laser host media because of its good optical, thermal, chemical and mechanical properties. In particular, its thermal conductivity is twice as large as that of $Y_3Al_5O_{12}$(YAG).

However, $Y_2O_3$ single crystal has a high melting temperature of 2430°C and structural phase transition at 2280°C. It is extremely difficult to grow large-size high-quality $Y_2O_3$ single crystals. In 1999, Konoshima Che-

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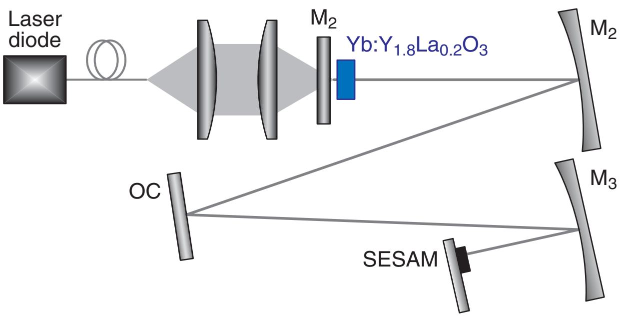


**Figure 1** (online color at www.lphys.org) Schematic of a diode-pumped Yb:$Y_{1.8}La_{0.2}O_3$ ceramic laser. $M_1$, $M_2$, and $M_3$ – cavity mirror; Yb:$Y_{1.8}La_{0.2}O_3$ – gain medium; OC – output coupler

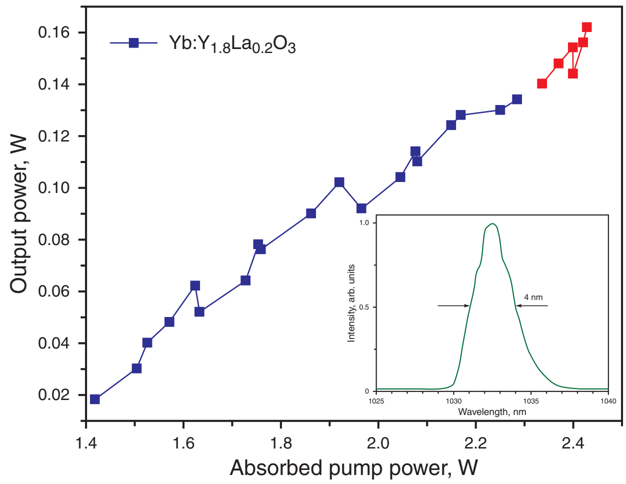


**Figure 2** (online color at www.lphys.org) Output power of CW mode-locked Yb:$Y_{1.8}La_{0.2}O_3$ ceramic laser versus non-lasing absorbed pump power by using 50 $\mu$m core-diameter diode laser

mical Co. Ltd in Japan reported a nano-crystalline and non-press vacuum sintering technology to fabricate high-quality, highly transparent and large-size $Y_2O_3$ceramic laser materials at a relatively low sintering temperature of 1700°C [27]. The sintering temperature could be further decreased to 1450 – 1650°C by adding $La_2O_3$ as a sintering aid in $Y_2O_3$ to form yttrium lanthanum oxide transparent ceramics Yb:$(Y_{1-x}La_x)_2O_3$ [28]. In the $(Y_{1-x}La_x)_2O_3$transparent ceramic matrix, the substitution of large $La^{3+}$ ion in $Y^{3+}$ ion sites induces a distorted crystalline lattice and a weak crystal field, resulting in weak interaction between $Yb^{3+}$ and $O^{2-}$ ions and lengthening the lifetime of $Yb^{3+}$ ions. This actually favors enhanced energy storage for high-power laser operation [29]. Efficient and broadband tunable continuous-wave (CW) Yb:$(Y_{1-x}La_x)_2O_3$ ($x = 0.1$) ceramic lasers have been realized at a very low lasing threshold under high-power diode pumping. A slope efficiency of 52% was achieved on an uncoated 5 at.% Yb-doped $Y_{1.8}La_{0.2}O_3$ ceramic [29]. In this letter, we demonstrate, for the first time to our knowledge, a diode-pumped passively mode-locked Yb:$(Y_{1-x}La_x)_2O_3$ ($x = 0.1$) ceramic laser, generating 174-ps pulses with an average power of 162 mW.

## 2. Experiment setup and results

Transparent Yb:$(Y_{1-x}La_x)_2O_3$ ceramic samples were fabricated with nano-powders and sintered at 1650°C for 50 h in $H_2$ atmosphere. A $Y_{1.8}La_{0.2}O_3$ ceramic with 5 at.% $Yb^{3+}$doping was cut as 1.5-mm long, 3×3 mm$^2$ in aperture (with no antireflection-coatings on both surfaces) for laser experiments, which were carried out with a Z-shaped resonator as schematically shown in Fig. 1. The laser cavity consists of a semiconductor saturable absorber mirror (SESAM) and three mirrors: an input flat mirror $M_1$ with high transmission at 974 nm and high reflection in a broad band from 1020 to 1120 nm, two folded concave mirrors $M_2$ (R = 500 mm) and $M_3$ (ROC = 200 mm) both high reflection in a broad band from 1020 to 1120 nm, and an output coupler (OC) flat mirror with a transmission of 2.5%. The length between $M_1$ and $M_2$ is about 251 mm, while $M_2$ and OC are separated by 448 mm, and the length between OC and SESAM is 939 mm. The total cavity length is added up to 1638 mm. The Yb:$Y_{1.8}La_{0.2}O_3$ ceramic was pumped by a 5-W fiber-coupled diode laser with a core diameter of 50 $\mu$m and a numerical aperture of 0.22 operated around 974 nm with a spectral bandwidth of 5 nm. The pump laser beam was focused by a series of lenses with a pump spot about 50 $\mu$m on the ceramic. The cavity mode radius in the gain medium was close to the pump beam radius. The Yb:$Y_{1.8}La_{0.2}O_3$ ceramic was placed near $M_1$ and mounted on a copper heat sink kept at 14°C to efficiently remove the generated heat under diode-pumping. Passive mode-locking is started with a SESAM (BATOP GmbH, Germany). The central wavelength of the SESAM in our experiment is 1064±5 nm. Around the central wavelength, the saturation fluence is 70 $\mu$J/cm$^2$, the saturation absorption is 2.0%, while the non-saturable loss is less than 0.3%. And the relaxation time is as short as 20 ps. In comparison with the so-called Kerr-lens mode-locking technique commonly used in ultrashort pulse lasers, SESAM-based mode-locking offers advantages such as release of critic requirements of precise cavity design and alignment, and ease in self-starting mode-locking. The laser beam was focused onto the SESAM by a concave mirror ($M_3$) with the fold angle of 5°. The mode-locked pulse train was detected by a fast photodiode with a rising time of less than 200 ps and recorded with a digital storage oscilloscope. Although the long fluorescent lifetimes of Yb-doped materials are advantageous for energy storage and make it suitable for high-power laser output, there exist a strong tendency towards Q-switching or Q-switched mode-locking. The resonator was carefully designed to suppress the strong tendency towards Q-switching or Q-switched mode-locking.

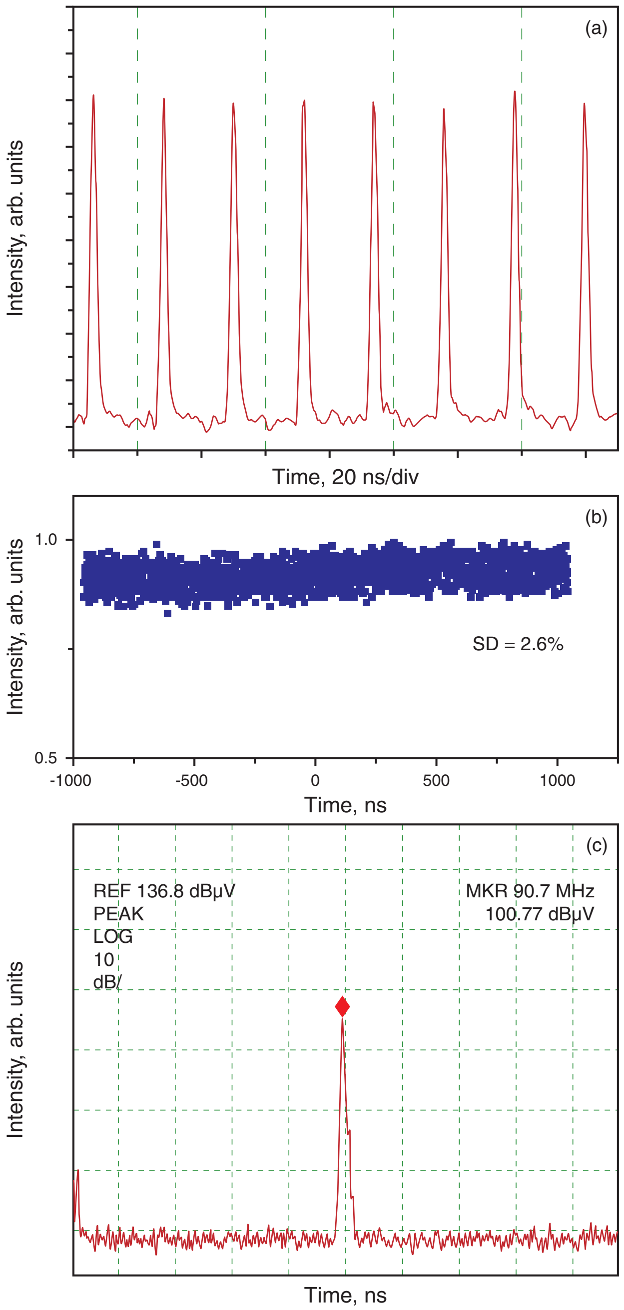


**Figure 3** (online color at www.lphys.org) (a) – the 90.7-MHz repetition rate of the CW mode-locked Yb:$Y_{1.8}La_{0.2}O_3$ ceramic laser pulses; (b) – the standard deviations of the CW mode-locked Yb:$Y_{1.8}La_{0.2}O_3$ ceramic laser pulse train; (c) – power spectrum of a CW mode-locked Yb:$Y_{1.8}La_{0.2}O_3$ ceramic laser

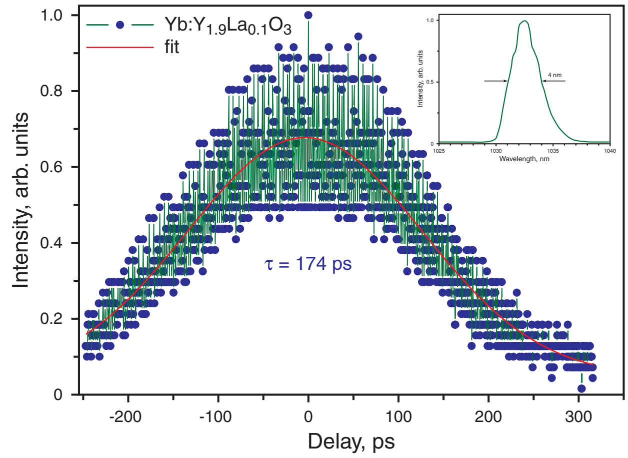


**Figure 4** (online color at www.lphys.org) Autocorrelation trace of the CW mode-locked Yb:$Y_{1.8}La_{0.2}O_3$ ceramic laser. The inset gives the corresponding spectrum of the 174 ps pulse

Stable CW mode-locked operation was obtained with an OC transmission of 2.5%. In our Yb:$Y_{1.8}La_{0.2}O_3$ ceramic laser, the strong tendency toward Q-switched mode-locking was suppressed by choosing a proper intracavity laser beam spot-size diameter on the SESAM. Fig. 2 shows the average output power measured for CW mode-locked lasers with a 2.5% OC as a function of the non-lasing absorbed pump power. The Yb:$Y_{1.8}La_{0.2}O_3$ ceramic laser changed from the CW operation to the CW mode-locked operation at a threshold pump power of 2.34 W (non-lasing absorbed pump power). With the maximum available power of our 50 $\mu$m diode pump (a non-lasing absorbed pump power of 2.43 W), an average output power of 162 mW was obtained. The corresponding slope efficiency was approximately 13%. No changes of the slope efficiency were observed as the ceramic laser was switched from the CW to CW mode-locking operation, indicating that intra-cavity beam geometry was not significantly changed. Even though the intra-cavity laser peak intensity was enhanced under mode-locking condition, nonlinear self-focusing or defocusing played a negligible role in modifying the intra-cavity beam trace, and nonlinear absorption of SESAM dominated in self-starting mode-locking. The nonlinear Kerr effects on the ceramic were probably shaded by the thermal defocusing, and the laser intensity should be increased to get observable Kerr effects inside the ceramic laser cavity. The CW mode-locked pulses were centered at 1032 nm with a spectral full-width of half-maximum (FWHM) about 4.0 nm. The spectral profile of the CW mode-locked output pulses is shown in the inset of Fig. 2. The CW mode-locked laser output pulse train was recorded with a digital oscilloscope with 1 GHz bandwidth (Agilent 54833A DSO), as shown in Fig. 3a. The shot-to-shot fluctuation of the mode-locked operation was monitored by observing the output pulse train. The long-term mode-locking stability was monitored by checking the output pulse energy. The standard deviations of the CW mode-locked Yb:$Y_{1.8}La_{0.2}O_3$ ceramic laser pulses are shown in Fig. 3b. With a careful alignment of the laser cavity under the 50-$\mu$m diode pump, the CW mode-locked laser has a slight pulse-to-pulse intensity fluctuation as a standard deviation of 2.6%. The pulse power spectrum is shown in Fig. 3c recorded by a spectral analyzer (Agilent E4411B), which clearly shows that the CW mode-locked laser was stably operated at 90.7 MHz. As shown in Fig. 4, the intensity autocorrelation of the CW mode-locked Yb:$Y_{1.8}La_{0.2}O_3$ ceramic laser measured with a home-made autocorrelator is well-fitted assuming a Guassian pulse shape as presented in Fig. 4. The FWHM duration of the pulse is about 174 ps. This is to the best of our knowledge the first demonstration of a CW mode-locked Yb:$Y_{1.8}La_{0.2}O_3$ ceramic laser.

The main absorption bands in Yb:$Y_{1.8}La_{0.2}O_3$ ceramic are centered at 904, 948, and 974 nm, attributing to the $^2F_{7/2}-^2F_{5/2}$ transition of $Yb^{3+}$ [10], among which the strongest absorption near 974 nm is well-matched with our high-brightness pump diode laser. The CW laser threshold was about 1.4 W (non-lasing absorbed pump power), higher than the 400-mW pumping threshold previously realized at 1080 nm under the same diode-pumping [29]. This was caused by the cross-section difference of different emission bands and the large intra-cavity losses due to the SESAM and large cavity length. The ceramic emission spectrum exhibits two main emission bands around 1033 and 1078 nm, corresponding to transitions between the ground state $^2F_{7/2}$ and the sub-levels of $^2F_{5/2}$, respectively, and an emission valley within 1050–1070 nm. This agrees well with the tunable curves of diode-pumped Yb:$Y_{1.8}La_{0.2}O_3$ ceramic laser [10]. Without SESAM, the CW laser tends to oscillate around the emission band at 1078 nm instead of 1030 nm due to the strong re-absorption at 1030 nm of the $Yb^{3+}$ ion although the emission cross-section around 1030 nm is larger than that around 1078 nm. While the SESAM used in our experiment (with the working wavelength around 1064 nm) forced the laser oscillate around 1030 nm.

## 3. Conclusion

In conclusion, we have demonstrated what we believe is the first diode-pumped CW mode-locked Yb:$Y_{1.8}La_{0.2}O_3$ ceramic laser, which is fabricated by low temperature. A maximum average output power of 162 mW was obtained at 1032 nm as Yb:$Y_{1.8}La_{0.2}O_3$ ceramic laser was continuous-wave mode-locked with a repetition rate of 90.7 MHz. We believe that femtosecond $Yb^{3+}$-doped yttrium lanthanum oxide transparent ceramic laser can be realized with optimized laser cavity and mode-locking elements.

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## References

[1] N.E. Bykovsky and Yu.V. Senatsky, Laser Phys. Lett. **5**, 664 (2008).
[2] H. Luo, D.Y. Tang, G.Q. Xie, H.J. Zhang, L.J. Qin, H.H. Yu, and L.J. Qian, Laser Phys. Lett. **5**, 651 (2008).
[3] J. Liu, H. Yang, H. Zhang, X. Mateos, V. Petrov, and J. Wang, Laser Phys. Lett. **5**, 874 (2008).
[4] A. Major, R. Cisek, D. Sandkuijl, and V. Barzda, Laser Phys. Lett. **6**, 272 (2009).
[5] Q. Liu, F. Lu, M. Gong, C. Li, and D. Ma, Laser Phys. Lett. **4**, 30 (2007).
[6] Q. Liu, X. Fu, D. Ma, X. Yan, F. He, L. Huang, M. Gong, and D. Wang, Laser Phys. Lett. **4**, 719 (2007).
[7] K. Sueda, S. Kawato, and T. Kobayashi, Laser Phys. Lett. **5**, 271 (2008).
[8] J. Dong, A. Shirakawa, and K. Ueda, Laser Phys. Lett. **4**, 109 (2007).
[9] W. Li, H. Pan, L. Ding, H. Zeng, W. Lu, G. Zhao, C. Yan, L. Su, and J. Xu, Appl. Phys. Lett. **88**, 221117 (2006).
[10] 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).
[11] W. Li, Q. Hao, H. Zhai, H. Zeng, W. Lu, G. Zhao, L. Zheng, L. Su, and J. Xu, Opt. Express **15**, 2354 (2007).
[12] A.S. Kurkov, E.M. Sholokhov, and O.I. Medvedkov, Laser Phys. Lett. **6**, 135 (2009).
[13] J. Li, K. Ueda, A. Shirakawa, M. Musha, L. Zhong, and Z. Zhang, Laser Phys. Lett. **4**, 814 (2007).
[14] S.W. Harun, S.D. Emami, F. Abd Rahman, S.Z. Muhd-Yassin, M.K. Abd-Rahman, and H. Ahmad, Laser Phys. Lett. **4**, 601 (2007).
[15] V.M. Paramonov, A.S. Kurkov, O.I. Medvedkov, and V.B. Tsvetkov, Laser Phys. Lett. **4**, 740 (2007).
[16] S.A. Babin, D.V. Churkin, A.E. Ismagulov, S.I. Kablukov, and M.A. Nikulin, Laser Phys. Lett. **4**, 428 (2007).
[17] A.S. Kurkov, V.V. Dvoyrin, V.M. Paramonov, O.I. Medvedkov, and E.M. Dianov, Laser Phys. Lett. **4**, 449 (2007).
[18] A.S. Kurkov, Laser Phys. Lett. **4**, 93 (2007).
[19] Y.X. Wang, D.Z. Yang, P.P. Jiang, and Y.H. Shen, Laser Phys. Lett. **6**, 461 (2009).
[20] M. Gong, B. Peng, Q. Liu, and P. Yan, Laser Phys. Lett. **5**, 733 (2008).
[21] J.A. Alvarez-Chavez, A. Martínez-Rios, I. Torres-Gomez, and H.L. Offerhaus, Laser Phys. Lett. **4**, 880 (2007).
[22] C. Ye, P. Yan, L. Huang, Q. Liu, and M. Gong, Laser Phys. Lett. **4**, 376 (2007).
[23] P.P. Jiang, D.Z. Yang, Y.X. Wang, T. Chen, B. Wu, and Y.H. Shen, Laser Phys. Lett. **6**, 384 (2009).
[24] Q. Hao, W. Li, and H. Zeng, Opt. Express **15**, 16754 (2007).
[25] J. Dong, K. Ueda, H. Yagi, A.A. Kaminskii, and Z. Cai, Laser Phys. Lett. **6**, 282 (2009).
[26] K. Takaichi, H. Yagi, P. Becker, A. Shirakawa, K. Ueda, L. Bohatý, T. Yanagitani, and A.A. Kaminskii, Laser Phys. Lett. **4**, 507 (2007).
[27] K. Takaichi, H. Yagi, J. Lu, J.-F. Bisson, A. Shirakawa, K. Ueda, T. Yanagitani, and A.A. Kaminskii, Appl. Phys. Lett. **84**, 317 (2004).
[28] Q.H. Yang, J. Ding, H.W. Zhang, and J. Xu, Opt. Commun. **273**, 238 (2007).
[29] Q. Hao, W. Li, H. Zeng, Q. Yang, C. Dou, H. Zhou, and W. Lu, Appl. Phys. Lett. **92**, 211106 (2008).