Dissipative soliton operation in diode pumped ultrafast Yb:GdYSiO$_5$ oscillator

Wenlong Tian (田文龙)[1], Jiangfeng Zhu (朱江峰)[1], Zhaohua Wang (王兆华)[2], Junli Wang (王军利)[1], and Zhiyi Wei (魏志义)[1,2*]

[1]*School of Technical Physics and Optoelectronics Engineering, Xidian University, Xian 710071, China*

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

**Corresponding author: zywei@iphy.ac.cn*

Received December 14, 2013; accepted January 15, 2014; posted online February 28, 2014

We demonstrate the dissipative soliton mode locking in a diode pumped Yb:GdYSiO$_5$(Yb:GYSO) laser operating in the positive dispersion regime. We obtain stable passively mode-locked pulses with strong positive chirp and with very steep spectral edges. The central wavelength is 1050 nm with bandwidth of about 4 nm, autocorrelation trace shown the typical pulse duration is about 3.5 ps. We obtain the maximum average power of 558 mW for a 3.3-W absorbed pump power, with 22% slope efficiency, and a 78-MHz pulse repetition frequency.

OCIS codes: 140.3480, 140.3615, 140.4050.

doi: 10.3788/COL201412.031401.

In recent years, the development of Yb^{3+} doped materials has generated considerable interest with the remarkable development of high brightness and high power InGaAs laser diodes emitting in the 900−980-nm range. It is because that Yb^{3+} compared to Nd^{3+} processes a much simpler electronic level structure composed of only two manifolds $^2F_{5/2}$ and $^2F_{7/2}$, so that most of undesired effects such as up-conversion, excited-state absorption, cross relaxation or concentration quenching are absented, leading to low thermal load as well as low quantum defect. Moreover, its relatively large emission bandwidth makes it possible to generate ultra-short pulses down to several tens of fs duration. Hence, Yb^{3+}-doped laser materials have great potential to be excellent laser mediums for high-power and ultrafast laser generation. However, most of Yb^{3+}-doped solid-state laser oscillators generating femtosecond pulses[1−4] are usually operating in the negative dispersion regime in which the balance between negative cavity dispersion and self-phase modulation (SPM) results in stable mode-locked pulses. This type of mode-locking in which nonlinear Schrödinger equation (NLSE) type solitons are existed has a drawback that the achievable pulse energy is restricted by the soliton area theorem. The pulse energy will decline as the inducing of net cavity dispersion. In order to obtain mode-locking pulses with higher pulse energy, ytterbium based chirped-pulse oscillator (CPO) which is operated in positive dispersion regime is of great interest in recent years[5−10]. Kalashinikov *et al.*[11] demonstrated that the chirped pulses generated in CPOs are chirped solitons and in effect dissipative solitons (DSs). The existence of DSs was firstly reported by Chong *et al.*[12,13] independently in an all-normal Yb and Er-doped fiber laser, respectively. Compared to NLSE solitons, DSs possess several distinctive features such as that they have much larger pulse energy than NLSE solitons and the spectra of them has steep spectral edges and the pulses are strongly chirped. Recently, Tan *et al.*[14] experimentally demonstrated the first dissipative soliton operation in Yb–doped solid state lasers. It was shown that DS operation existed in the positive cavity dispersion mode-locking regime of the Yb doped solid-state lasers. Though, there are few reports of dissipative soliton operation of the Yb^{3+} based mode-locking solid-state bulk laser.

As a new laser material, a lot of excellent results have been reported in Yb:GYSO. Du *et al.*[15] reported the first demonstration on the efficient tunable continuous wave (CW) operation of a Yb:GYSO laser in 2006. Zhou *et al.*[16] demonstrated a 210-fs laser operation at 1093 nm pumped by a continuous wave (CW) Ti:sapphire laser in 2009. He *et al.*[17] realized both soliton and non-soliton mode-locked Yb:GYSO lasers in 2011. Most recently, we implemented a laser diode pumped passively mode-locked Yb:GYSO laser generating 324 fs at 1091 nm[18]. In this letter, we report the DS operation in a diode pumped Yb:GYSO laser with stable mode-locking operation at the central wavelength of 1050 nm. The maximum output power was 558 mW. Laser action was utilized with a 3-mm-long, antireflection-coated, and 5 at.-% doped Yb:GYSO crystal as the laser gain medium. The Yb:GYSO was wrapped with indium foil and mounted tightly on a water-cooled copper heat sink block. The copper block was cooled by flowing water which was maintained at 12 °C during the experiment. The laser crystal was end-pumped by a high brightness fiber-coupled diode laser emitting at 976 nm with the maximum output power of 7 W (JOLD-7.5-BAFC-105, Jenoptik, Germany). The core diameter of the fiber is 50 μm and the numerical aperture (NA) is 0.22. We used an imaging system with a magnification of 0.8 to couple the pump laser output from the fiber into the Yb:GYSO crystal. At first, we characterized the laser action in CW operation. A sketch of experimental setups is shown in Fig. 1(a). M1 was a plane dichroic mirror which was coated with high reflection in the range of 1020−1100 nm

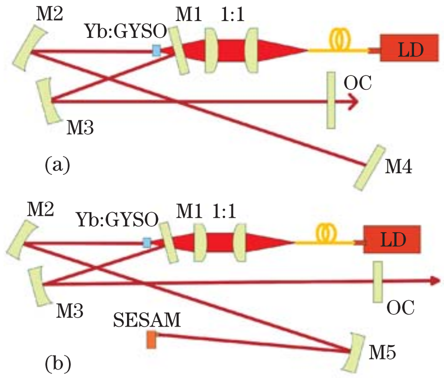

Fig. 1. (Color online) Experimental diagrams of the (a) CW and (b) DS mode-locking Yb:GYSO lasers.

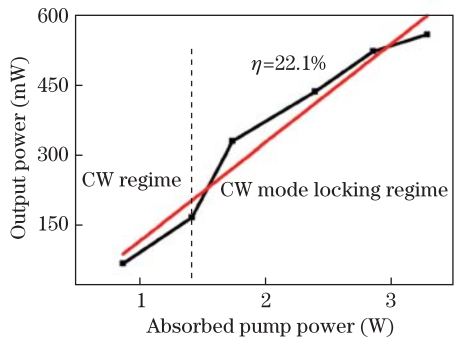

Fig. 2. (Color online) Output power versus absorbed power.

and high transmission at 970−980 nm; Both M2 and M3 were curved folding mirrors and had a high reflectivity at 1020−1100 nm with 200- and 300-mm radius of curvature (ROC), respectively; M4 was an end mirror with high reflection in the range of 1020−1100 nm. The output coupler (OC) was a plane mirror with a 0.8% transmission at 1020−1100 nm. The threshold pump power for CW laser generation was as low as 120 mW. We obtained the highest CW output power of 1.3 W under 3.3-W absorbed pump powers, corresponding to a 42.8% slope efficiency.

The mode-locking operation was realized with a standard confocal cavity depicted in Fig. 1(b). To initiate the mode locking, we replaced M4 with a semiconductor saturable absorber mirror (SESAM; BATOP, Germany) with a 0.4% modulation depth at 1064 nm, a 90-μJ/cm^2 saturation fluence, and a 500-fs relaxation time. The laser beam was focused onto the SESAM by a curved folding mirror M5 with 300-mm ROC. The total cavity length was 1.92 m which corresponding to a repetition rate of about 78 MHz.

With optimization of the cavity alignment, we achieved stable mode-locking operation which was self-starting when absorbed pump power was above 1.4 W with an OC of T=0.8% as shown in Fig. 2. The maximum mode-locked output power obtained was 558 mW when absorbed pump power was 3.3 W and the corresponding slope efficiency was 22%. Figure 3 describes the optical spectra of the mode-locked pulse under three different incident pump powers. The apparent characteristic of the mode-locking spectra realized is that the edges are extremely sharp as well as steep. We also observed that the edge-to-edge spectral bandwidth declines with pump power decreases and attributed this result to the operation of DS. Without any intra-cavity dispersion compensation element, a 4-nm full-width at half-maximum (FWHM) bandwidth was obtained with wavelength centered at 1050 nm. The bandwidth of the optical spectra obtained is able to support femtosecond pulses with duration of 290 fs if a sech^2-shaped pulse is assumed. In a previous publication we implemented the NLSE type soliton mode-locked Yb:GYSO laser using a similar cavity structure but with a pair of SF6 prisms to compensate the intracavity dispersion[18]. The mode-locking pulses possess a pulse duration of 324 fs and a pulse energy of 5.6 nJ under nearly the same pulse repetition rate, which is smaller than the pulse energy of 7.2 nJ achieved here. It is shown that operating Yb:GYSO in positive dispersion regime allows to generate mode-locking pulses with larger pulse energy.

Intensity autocorrelation trace shown in Fig. 4 was also measured by a commercial intensity autocorrelator (FR-103MN, Femtochrome Research, Inc., USA). The mode-locked pulse duration was 3.5 ps, if a sech^2-pulse shape was assumed. The corresponding time-bandwidth product was 3.8 which was 12 times the value of the transform limited sech^2-pulse (0.315). The character of strong chirp further shows the dissipative soliton operation in the Yb: GYSO oscillator.

In conclusion, the first DS operation in a Yb:GYSO laser oscillator pumped by laser diode is demonstrated. We obtain stable mode-locking pulses with a 4-nm FWHM at the 1050-nm central wavelength. We believe

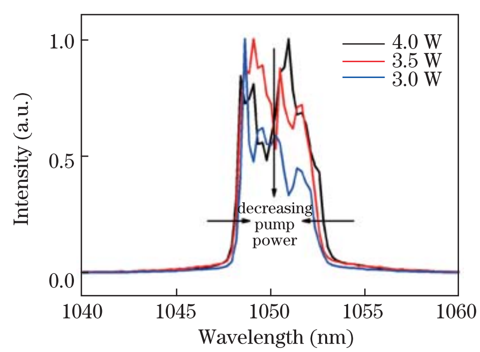

Fig. 3. (Color online) Optical spectra of the DS mode-locking pulses under three different pump powers (3, 3.5, and 4 W).

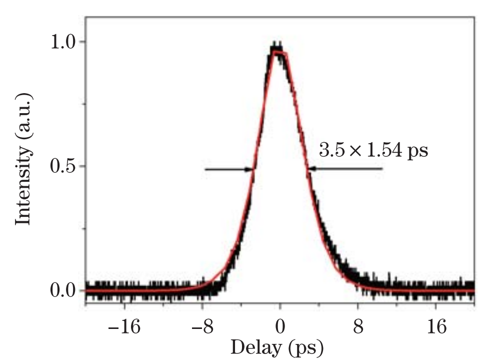

Fig. 4. (Color online) Intensity autocorrelation trace of the DS mode-locking pulses. The experimental data and the sech^2 fitting curve are described by the black curve and the red curve, respectively.

that a pulse with duration under 400 fs can be obtained by extra cavity dispersion compensation in the future. The maximum output power obtained is 558 mW and the corresponding slope efficiency is 22%. Much higher output power and pulse energy can be obtained by using an OC of higher transmission. These results show that the Yb:GYSO crystal to be an excellent laser medium for generating femtosecond pulses with high power and high pulse energy.

This work was supported by the National "973" Program of China (No. 2013CB922402), the National Key Scientific Instruments Development Program of China (No.2012YQ120047), and the National Natural Science Foundation of China (No. 61205130). We thank Prof. Jun Xu and Prof. Liangbi Su for supplying us the Yb:GYSO crystal for the experiment and helpful discussion with Prof. Xiaodong Zeng.

References

1. J. Zhu, Z. Wang, Q. Wang, Z. Zhang, Q. Yang, J. Yang, Y. Ma, and Z. Wei, Chin. Opt. Lett. **10,** 121403 (2012).
2. A. Yoshida, A. Schmidt, V. Petrov, C. Fiebig, G. Erbert, J. Liu, H. Zhang, J. Wang, and U. Griebner, Opt. Lett. **36,** 4425 (2011).
3. S. Uemura, Jpn. J. Appl. Phys. **50,** 010201 (2011).
4. A. Agnesi, A. Greborio, F. Pirzio, G. Reali, J. Aus der Au, and A. Guandalini, Opt. Express **20,** 10077 (2012).
5. G. Palmer, M. Emons, M. Siegel, A. Steinmann, M. Schultze, M. Lederer, and U. Morgner, Opt. Express **15,** 16017 (2007).
6. G. Palmer, M. Schultze, M. Siegel, M. Emons, A. Steinmann, and U. Morgner, in *Proceedings of Advanced Solid State Photonics* MC2 (2009).
7. G. Palmer, M. Schultze, M. Emons, A. L. Lindemann, M. Pospiech, D. Steingrube, M. Lederer, and U. Morgner, Opt. Express **18,** 19095 (2010).
8. S. Uemura and K. Torizuka, in *Proceedings of Advanced Solid State Photonics* AWB25 (2010).
9. S. Uemura and K. Torizuka, in *Proceedings of 2013 Conference on Lasers and Electro-Optics Pacific Rim (CLEO-PR)* WPA-4 (2013).
10. V. L. Kalashnikov and A. Apolonski, in *Proceedings of Advanced Solid State Lasers* JTH2A.34 (2013).
11. V. L. Kalashnikov, A. Fern'andez, and A. Apolonski, Opt. Express **16,** 4206 (2008).
12. A. Chong, J. Buckley, W. Renninger, and F. Wise, Opt. Express **14,** 10095 (2006).
13. L. M. Zhao, D. Y. Tang, and J. Wu, Opt. Lett. **31,** 1788 (2006).
14. W. D. Tan, D. Y. Tang, C. W. Xu, J. Zhang, X. D. Xu, D. Z. Li, and J. Xu, Opt. Express **19,** 18495 (2006).
15. J. Du, X. Liang, Y. Xu, R. Li, Z. Xu, C. Yan, G. Zhao, L. Su, and J. Xu, Opt. Express **14,** 3333 (2006).
16. B. Zhou, Z. Wei, Y. Zhang, X. Zhong, H. Teng, L. Zheng, L. Su, and J. Xu, Opt. Lett. **34,** 31 (2009).
17. J. He, X. Liang, J. Li, L. Zheng, L. Su, and J. Xu, Chin. Phys. Lett. **28,** 084204 (2011).
18. J. F. Zhu, W. L. Tian, J. L. Wang Z. Y. Wei, L. H. Zheng, L. B. Su, and J. Xu, Opt. Lett. **37,** 5190 (2012).