Passively Q-switched erbium-doped fiber laser using Fe$_3$O$_4$-nanoparticle saturable absorber

Xuekun Bai$^1$, Chengbo Mou$^{1,2,*}$, Luxi Xu$^1$, Shaofei Wang$^1$, Shengli Pu$^3$, and Xianglong Zeng$^1$*

$^1$The Key Lab of Specialty Fiber Optics and Optical Access Network, Shanghai University, 200072 Shanghai, China
$^2$Aston Institute of Photonic Technologies (AIPT), Aston University, Birmingham B4 7ET, U.K.
$^3$College of Science, University of Shanghai for Science and Technology, 200093 Shanghai, China

*E-mail: mouc1@shu.edu.cn; zenglong@shu.edu.cn

Received January 21, 2016; accepted February 16, 2016; published online March 4, 2016

We experimentally demonstrate passively Q-switched erbium-doped fiber laser (EDFL) operation using a saturable absorber (SA) based on Fe$_3$O$_4$ nanoparticles (FONPs). As a type of transition metal oxide, the FONPs have a large nonlinear optical response and fast response time. The FONP-based SA possesses a modulation depth of 8.2% and nonsaturable absorption of 56.6%. Stable passively Q-switched EDFL pulses with an output pulse energy of 23.76 nJ, a repetition rate of 33.3 kHz, and a pulse width of 3.2 µs were achieved when the input pump power was 110 mW. The laser features a low threshold pump power of ∼15 mW. © 2016 The Japan Society of Applied Physics

---

Q-switched erbium-doped fiber lasers (EDFLs) are useful light sources owing to their potential applications in remote sensing, range finding, laser processing, optical communications, the military, and so on.1,2 Compared with active Q-switching, passive Q-switching based on light intensity saturable absorbers (SAs) possesses the advantages of compactness, low cost, and a simple cavity configuration. Various types of functional materials are reportedly used as SAs to achieve passive Q-switching, such as graphene,3) gold nanorods,4,5) carbon nanotubes,2,6) Bi$_2$Se$_3$,7) MoS$_2$,8) WS$_2$,9,10) MoSe$_2$,11,12) and black phosphorus.13) In addition, exploration of new SA materials for passive Q-switched EDFLs is still attractive.

Fe$_3$O$_4$ nanoparticles (FONPs) show remarkable and interesting physical properties, including super-paramagnetism, high field irreversibility, and extra anisotropy contributions because of their finite size and surface effects.15) FONPs show great potential in a variety of applications including medical applications,16) microwave devices,17) magneto-optical devices,18–21) and magnetic field sensors.22,23) Furthermore, FONPs exhibit nonlinear photonic properties such as two-photon absorption,24) optical limiting,25) and nonlinear scattering.26) As a type of transition metal oxide, FONPs show a large third-order optical nonlinear susceptibility $\chi^{(3)}$,27) indicating a large nonlinear optical response for many applications.28–30) Further, the recovery time of FONPs was evaluated as 18–30 ps.30) Recently, an energy band gap in FONPs was observed, so such materials can be classified as a type of semiconductor.31,32) The band gap energy of FONPs can be tuned by selecting the diameter of the nanoparticles,31) which is finely controlled by adjusting the pH and ionic strength of the precipitation medium during preparation.15,32) Therefore, FONPs are claimed to be a novel type of promising nonlinear optical material that may find wide potential applications in photonics.

In this work, we propose and demonstrate an all-fiber passively Q-switched EDFL using an FONP-based nonlinear optical SA. The fabrication of an FONP-based SA device is quite simple and straightforward. Compared to other types of SA, the feature of controllable band energy is highlighted in the FONP-based device and may play a key role in implementing an SA with a predefined and optimized saturation intensity, operation bandwidth, and non-bleachable loss.
FONP-based SA device. (a) Measured linear absorption and (b) saturable absorption of the FONP-based SA is illustrated in Fig. 2. The FONP-based SA has a broad absorption band (1438–1628 nm). The linear absorption of the FONP-based SA is ∼63% at a wavelength of 1560 nm. This linear loss may be reduced effectively by further optimizing the thickness and uniformity of the FONP film or using an FONP-coated tapered or polished fiber. Because of the finite thickness of the SA film between the two optical fiber ferrules, an interference pattern can be seen clearly in the measured absorption spectrum. The visibility of SA-induced interference is relatively small (less than 5%), so it can be neglected in the fiber laser cavity. The measured insertion loss of the SA is about 4.1 dB. The nonlinear absorption property of the FONP-based SA is investigated using balanced twin-detector measurement. The saturable absorption data are fitted using the formula $T(I) = 1 - \Delta T \exp(-I/I_{sat}) - T_{ns}$, as shown in Fig. 2(b), where $T(I)$ is the transmission, $\Delta T$ is the modulation depth, $I$ is the input intensity, $I_{sat}$ is the saturation power intensity, and $T_{ns}$ is the nonsaturable absorbance. The modulation depth, saturation intensity, and nonsaturable absorbance are found to be 15.758%, 56.207%, and 21.255 MW/cm², respectively. The main contribution to the saturable absorption of the FONPs could be the third-order nonlinear absorption of the FONPs.

Figure 3 shows a schematic of the construction of the passively Q-switched EDFL incorporating the FONP-based SA. The red arrow indicates the light propagation direction in the laser cavity. An EDF 7.5 m in length (Nufern EDFC-980-HP) is pumped by a 980 nm laser diode through a 980/1550 nm wavelength division multiplexing (WDM) coupler. The dispersion of the EDF used in this experiment has a nominal absorption of 6.0 ± 1.0 dB/m at 1530 nm with a group velocity dispersion (GVD) of +15.5 ps²/km at 1550 nm. The pigtail fiber (Corning HICER98) of the WDM couplers is ∼1.86 m long and has a dispersion of −0.25 ps²/km at 1550 nm. An in-fiber polarization-independent isolator is utilized to force unidirectional operation of the laser cavity. At the laser output, 10% of the power is extracted from the laser cavity via a 90/10 coupler. The rest of the fibers in the laser ring cavity are only standard single-mode fibers (SMFs) with a typical GVD of ∼23 ps²/km at 1550 nm. The total length of the cavity is about 19.4 m, and the overall dispersion of the cavity is about −0.1 ps² at 1550 nm. A polarization controller is used in the cavity to optimize the cavity birefringence. The temporal and spectral characteristics of the Q-switched fiber laser output are recorded by a 10 GHz photodetector (Conquer KG-PD-10G-FP) followed by a 300 MHz oscilloscope (Tektronix DPO3032) and an optical spectrum analyzer (Yokogawa AQ6370C).

Passive Q-switching of the constructed fiber laser self starts at a pump power of 15 mW. Compared with previously reported results, the threshold power of this laser is relatively low, which is attributed to the larger third-order optical nonlinearities induced by the FONPs. The 3 dB bandwidth of the optical spectrum is measured to be 2.5 nm at the center wavelength of 1560 nm under pumping at 110 mW, as shown in Fig. 4(a). The optical spectrum is relatively broad compared with those in previously reported results. The reason is that the FONPs induced scattering effects. The measured average output power is ∼0.8 mW when a commercial power meter (Yiai AV6334) is used. The corresponding output pulse train indicates a repetition rate of 33.3 kHz and a measured pulse duration of 3.2 µs, as shown in Figs. 4(b) and 4(c), respectively.

Figure 5(a) shows the spectral evolution of the Q-switched output pulse under pump powers ranging from 15 to 110 mW in 10 mW steps. The corresponding measured 3 dB bandwidth of the spectrum increases from 0.38 to 2.5 nm at a rate of 0.02 nm/mW, as shown in Fig. 5(b). In the experiment, the pulse energy is found to change with increasing pump power, and the output power increases monotonously when more gain is provided to saturate the SA. The corresponding output power increased from 94 to 794 µW, and the single-pulse energy varied from 12.13 to 23.76 nJ, as shown in Fig. 5(c).
As the pump power increases, the pulse duration of the stable output pulses decreases from 20.0 to 3.2 µs, and the repetition rate increases monotonically from 7.8 to 33.3 kHz, as shown in Fig. 5(d). This finding also presents a typical feature of passively Q-switched lasers. When the pump rate for the upper laser level increases with increasing pump power, this can reduce the pulse width and increase the repetition rate.2,4) The demonstrated laser shows no obvious degradation under laboratory conditions for 2 h. In our experiment, no stable pulse trains are observed when the pump power exceeds 110 mW. The laser begins continuous wave (CW) operation when the pump power increases from 110 to 600 mW. If the pump power is reduced to 110 mW again, Q-switching reappears. This is because FONPs exhibit a saturable absorption at moderate intensity, but optical limiting induced by excited-state absorption would occur at higher intensity.25,30,33)

To verify the effects of the FONP-based SA on Q-switching, two optical fiber pigtails connected by a flange without FONPs are inserted in the EDFL cavity. The lengths of the corresponding SMFs are not changed. Only CW laser operation is obtained, and no pulsed operation is observed as the pump power is increased from 0 to 680 mW, which confirms that the Q-switched EDFL operation described above was induced by the FONP-based SA. Figures 6(a) and 6(b) present the measured emission spectrum of the EDFL and the laser intensity as a function of time for a pump power of 40 mW, respectively.

For a Q-switched fiber laser with a higher pulse energy output, a lower repetition rate and pump power are preferred because the intracavity power can be more effectively coupled to each pulse under these conditions. Although this pulse energy still cannot outperform that of a laser using conven-

---

**Fig. 4.** (a) Spectrum, (b) pulse train, and (c) profile of the Q-switched pulses.

**Fig. 5.** (a) Output spectrum, (b) corresponding 3 dB bandwidth, (c) average output power and single pulse energy, and (d) repetition rate and pulse width variation with increasing pump power.
tional semiconductor-based SAs, further improvement to scale up the pulse energy is foreseeable with this FONP-based SA by optimizing the fabrication procedure, especially the mean diameter of the FONPs and the thickness and uniformity of the MF film. Using a higher-gain active fiber and higher output coupling ratio in the cavity may also boost the output power. The lengths of the EDF and cavity need to be optimized to improve the output laser characteristics. Owing to the tunable magneto-optical properties of FONPs, the Q-factor tunability of Q-switching based on an all-fiber FONP SA could be controlled by an external magnetic field. The thermal effects of FONPs, which decrease the nonlinear absorption of the FONP-based SA, should be avoided. Potential photonics application of the FONP-based SA in mode locking by using the enhanced FONP-based SA and an optimized EDFL cavity will be investigated in future work. Further, to explore more ultrafast photonics applications, the relaxation dynamics of FONPs will be studied experimentally.

In conclusion, we investigated the nonlinear optical absorption of FONPs derived from an MF. An all-fiber passively Q-switched EDFL with an FONP-based SA was successfully demonstrated. The demonstrated laser features a low threshold due to the large third-order optical response and the fast response time of the FONP-based SA. The easy fabrication, good stability, and robust structure of the FONP-based SA will facilitate many more potential nonlinear photonic applications, which are expected to support work toward ultrafast photonics and play key roles in other nonlinear photonics applications.

Acknowledgments This work was supported by the National Natural Science Foundation of China (Grant No. 11274224). X. Zeng acknowledges the support of the Young Eastern Scholar program (QD2015027) at Shanghai Institutions of Higher Learning. C. Mou acknowledges the support of the Young Eastern Scholar program (QD2015027) at Shanghai Institutions of Higher Learning.

1) P. Pérez-Millán, J. L. Cruz, and M. V. Andrés, Appl. Phys. Lett. 87, 011104 (2005).
2) D. Zhou, L. Wei, B. Dong, and W. Liu, IEEE Photonics Technol. Lett. 22, 9 (2010).
3) D. Popa, Z. Sun, T. Hasan, F. Torrisi, F. Wang, and A. C. Ferrari, Appl. Phys. Lett. 98, 073106 (2011).
4) T. Jiang, Y. Xu, Q. Tian, L. Liu, Z. Kang, R. Yang, G. Qin, and W. Qin, Appl. Phys. Lett. 101, 151122 (2012).
5) D. Fan, C. Mou, X. Bai, S. Wang, N. Chen, and X. Zeng, Opt. Express 22, 18537 (2014).
6) X. Li, Y. Wang, Y. Wang, W. Zhao, X. Yu, Z. Sun, X. Cheng, X. Yu, Y. Zhang, and Q. Wang, Opt. Express 22, 17227 (2014).
7) Z. Yu, Y. Song, J. Tian, Z. Dou, Y. Guo, Y. He, K. Li, H. Li, and X. Zhang, Opt. Express 22, 11508 (2014).
8) K. F. Mak, C. Lee, J. Hone, J. Shan, and T. F. Heinz, Phys. Rev. Lett. 105, 136805 (2010).
9) R. I. Woodward, E. J. R. Kelleher, R. C. T. Howe, G. Hu, F. Torrisi, T. Hasan, S. V. Popov, and J. R. Taylor, Opt. Express 22, 31113 (2014).
10) Z. Luo, Y. Huang, M. Zhong, Y. Li, J. Wu, B. Xu, H. Xu, Z. Cai, J. Peng, and J. Weng, J. Lightwave Technol. 32, 4679 (2014).
11) P. Yan, A. Liu, Y. Chen, J. Wang, S. Ruan, H. Chen, and J. Ding, Sci. Rep. 5, 12587 (2015).
12) K. Wu, X. Zhang, J. Wang, X. Li, and J. Chen, Opt. Express 23, 11453 (2015).
13) R. I. Woodward, R. C. T. Howe, T. H. Runcorn, G. Hu, F. Torrisi, E. J. R. Kelleher, and T. Hasan, Opt. Express 23, 20051 (2015).
14) Y. Chen, G. Jiang, S. Chen, Z. Guo, X. Yu, C. Zhao, H. Zhang, Q. Bao, S. Wen, D. Tang, and D. Fan, Opt. Express 23, 12823 (2015).
15) P. Tartaj, M. del Puerto Morales, S. Veintemillas-Verdaguer, T. Gonzalez-Carrero, and C. J. Serna, J. Phys. D 36, R182 (2003).
16) T. Neuberger, B. Schöpf, H. Hofmann, M. Hofmann, and B. von Rechenberg, J. Magn. Magn. Mater. 293, 483 (2005).
17) G. Sun, B. Dong, M. Cao, B. Wei, and C. Hu, Chem. Mater. 23, 1587 (2011).
18) H. E. Horng, C. S. Chen, K. L. Fang, S. Y. Yang, J. J. Chieh, C.-Y. Hong, and H. C. Yang, Appl. Phys. Lett. 85, 5592 (2004).
19) A. Candiani, W. Margulis, C. Sterner, M. Konstantaki, and S. Pissadakis, Opt. Lett. 36, 2548 (2011).
20) R. Patel and R. V. Mehra, Appl. Opt. 50, G17 (2011).
21) J. Li, X. Liu, Y. Lin, L. Bai, Q. Li, and X. Chen, Appl. Phys. Lett. 91, 253108 (2007).
22) H. Wang, S. Pu, N. Wang, S. Dong, and J. Huang, Opt. Lett. 38, 3765 (2013).
23) H. Thakur, S. Nalawade, S. Gupta, R. Krittere, and S. Kale, Appl. Phys. Lett. 99, 161101 (2011).
24) D. Soga, S. Alves, A. Campos, F. A. Tourinho, J. Depeyrot, and A. M. F. Neto, J. Opt. Soc. Am. B 22, 49 (2007).
25) S. S. Nair, J. Thomas, C. S. Suchand Sandeep, M. R. Anantharaman, and R. Philip, Appl. Phys. Lett. 92, 171908 (2008).
26) C. P. Singh, K. S. Bindra, G. M. Bhalerao, and S. M. Oak, Opt. Express 16, 8440 (2008).
27) T. Hashimoto, T. Yoko, and S. Sakka, J. Ceram. Soc. Jpn. 101, 64 (1993).
28) M. Ando, K. Kadono, M. Haruta, T. Sakagushi, and M. Miya, Nature 374, 625 (1994).
29) T. Hashimoto, T. Yamada, and T. Yoko, J. Appl. Phys. 80, 3184 (1996).
30) G. Xing, J. Jiang, J. Y. Ying, and W. Ji, Opt. Express 18, 6183 (2010).
31) H. El Ghandour, H. M. Zidan, M. M. H. Khalil, and M. I. M. Ismail, Int. J. Electrochem. Sci. 7, 5372 (2012).
32) F. El-Diasty, H. M. El-Sayed, F. I. El-Hosiny, and M. I. M. Ismail, Curr. Optin. Solid State Mater. Sci. 13, 28 (2009).
33) A. P. Reena Mary, C. S. Suchand Sandeep, T. N. Narayanan, R. Philip, P. Moloney, P. M. Ajayan, and M. R. Anantharaman, Nanotechnology 22, 375702 (2011).