Q-switched Er-doped fiber laser with single-walled carbon nanotube saturable absorber by evanescent field

Xinzheng Dong (董信征), Jinrong Tian (田金荣)*, Zhenhua Yu (于振华), and Yanrong Song (宋晏蓉)

College of Applied Sciences, Beijing University of Technology, Beijing 100124, China

**Corresponding author: jrtian@bjut.edu.cn*

Received January 14, 2014; accepted March 15, 2014; posted online November 3, 2014

A Q-switched Er-doped all-fiber laser, based on a single-walled carbon nanotube saturable absorber (SA) is constructed. The SA with a modulation depth of 8% is prepared using a special chemical-corrosion method. Furthermore, the SA is introduced to an Er-doped all-fiber laser, and Q-switching is obtained successfully. The repetition rate of the Q-switched laser can be tuned continuously from 128 to 278 kHz with pulse widths from 1.92 μs to 488 ns. The maximum output power is 13.1 mW.

OCIS codes: 060.3510, 140.3540.

doi: 10.3788/COL201412.S21402.

Er-doped fiber lasers have been investigated for years owing to many potential applications such as optical communications systems, sensing, spectroscopy, and medicine[1]. Quite a few Q-switched Er-doped lasers near 1550 nm have been demonstrated for certain uses with actively Q-switched and passively Q-switched method[2]. Actively Q-switched lasers were performed using electro-optic, acousto-optic, or transmission-dependent intensity modulators in the cavity[3,4]. Passively Q-switched laser could be obtained using a saturable absorber (SA), such as carbon nanotube (CNT), graphene oxide, and semiconductor saturable absorber mirror (SESAM).

In recent years, new-type SAs based on single-walled carbon nanotubes (SWCNTs) have been developed and applied to fiber lasers and solid-state lasers for Q-switching or mode locking. The CNTs have shown many advantages in short absorption recovery times (< 1 ps), reasonable modulation depths, and simple modulation processes[5,6]. CNTs-based Q-switched or mode-locked fiber lasers near 1, 1.55, and 2 μm were reported in quite a few publications[7]. Typically, SWCNT-based SAs are placed in the cavity and the laser incidents on the absorber directly, which is simple for laser arrangement. However, the absorber may be destroyed for high-power laser[8,9]. In recent years, a new method was proposed, that is, SWCNT was spread on the surface of fiber clad in order for the interaction with laser in evanescent field, which will benefit greatly for high-power fiber lasers.

We demonstrated an evanescent-field-assisted Q-switched fiber laser. A SWCNTs-based SA was prepared using a special chemical-corrosion method and applied to a ring all-fiber Er-doped fiber laser, and Q-switching was obtained successfully.

The SA was prepared with SWCNTs by the chemical-corrosion method. The outside coating of the single-mode fiber was removed, and the naked clad was immerged into hydrofluoric so as to corrode the glass until the remainder of the cladding diameter was near 48 μm. Then 5 mg SWCNTs powder were poured into 10 mL, 0.1% sodium dodecyl sulfate aqueous solution, and SWCNTs aqueous solution was ultrasonically agitated for 5 h for uniform distribution of SWCNTs. The polyvinyl alcohol (PVA) solution was poured into the SWCNTs aqueous solution, and then the SWCNTs/PVA mixed solution was ultrasonically agitated for 5 h together. Finally, the well-dispersed SWCNTs/PVA mixed solution was spread on the corroded segment of the fiber. The SWCNTs/PVA films were prepared successfully after drying at 90 °C. The transmittance versus pump power was detected as shown in Fig. 1. The transmittance of the SWCNTs/PVA film increased from 51% to 59%, which corresponded to a modulation depth of 8%[10].

The configuration for the Q-switched Er-doped fiber laser is shown in Fig. 2. The all-fiber laser had a ring cavity length of 1.4 m. The pump near 980 nm was injected into a 0.4 m Er-doped fiber (core absorption rate: 60 dB/m at 980 nm) by a 980/1550 nm wavelength division multiplexer (WDM). A polarization controller (PC) was used intra-cavity to control the polarization state of the laser and to optimize the laser

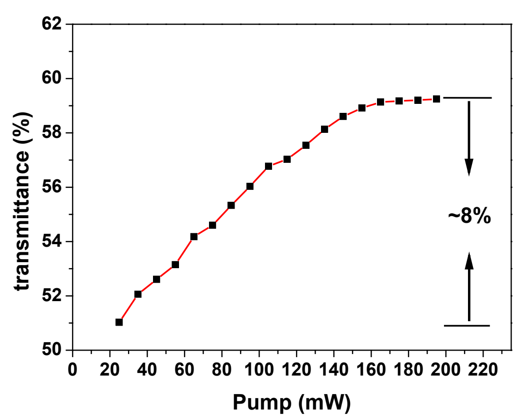

Fig. 1. Transmittance as a function of pump power.

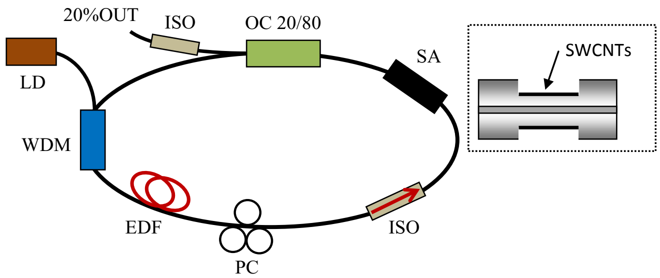

Fig. 2. Schematic of the Q-switch Er-doped fiber laser.

performance. A polarization-independent isolator (ISO) was used to force the laser to propagate unidirectionally followed by the prepared SA for Q-switching. A 20/80 output coupler (OC) was placed between SA and WDM to couple out 20% portion of the laser. To stabilize Q-switching, an ISO was used after OC to prevent the laser's back reflection.

When the pump power reached 40 mW, the continuous wave (CW) Er-fiber laser was oscillated at 1554 nm. By increasing the pump power, the laser would transform from CW to Q-switching at pump power rate of 110.9 mW. Increase in pump power led to increase in output power, while maintaining the Q-switching. Figure 3 shows the relation between output power and

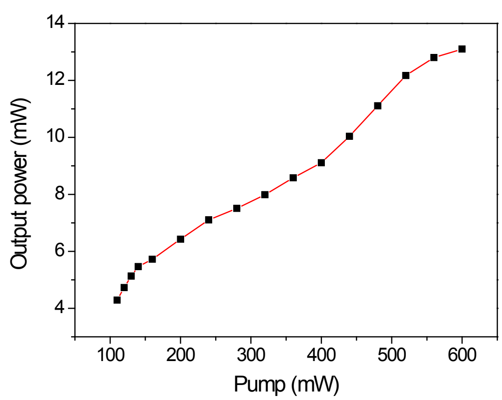

Fig. 3. Output power vs. pump power.

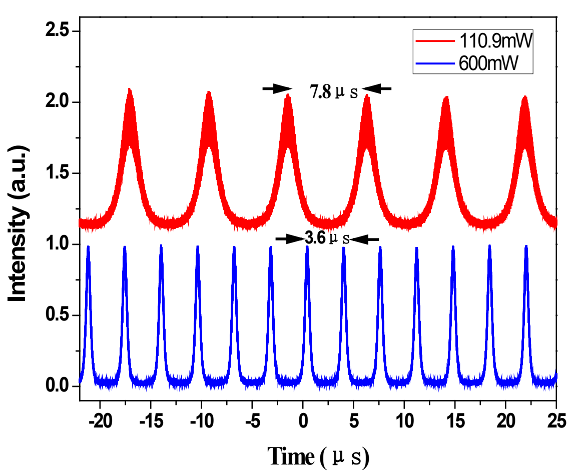

Fig. 4. Pulse trains of the Q-switched laser at 110.9 and 600 mW.

pump power, and the maximum output power was 13.1 mW at the pump power of 600 mW (limited by the maximum output power of the pump diode). It is noteworthy that the output power level had a certain relationship with the remaining fiber cladding diameter of the SA, because part of the light in fiber core would leak, causing some losses. If the corrosion time was controlled more precisely for a more suitable fiber cladding diameter, we believe a higher output power could be obtained.

The output laser was injected into a photodiode and the pulse trains of Q-switched pulse were observed by an oscilloscope (Infiniium 54833A, Agilent, USA). Figure 4 shows a typical result at the pump power of 110.9 and 600 mW, respectively. At pump power of 110.9 mW, the pulse interval was 7.8 μs, corresponding to a repetition rate of 128 kHz and the pulse width is 1.92 μs. At pump power of 600 mW, the pulse interval was 3.6 μs, corresponding to a repetition rate of 278 kHz and the pulse width is 488 ns. The pulse width would be shortened with increasing repletion rate, which was consistent with the result of the Q-switched laser. During the experiment, the pulse width from 488 ns to 1.92 μs could be obtained by controlling the pump power, and the narrowest width of 488 ns was obtained with pump power at 600 mW as shown in Fig. 5.

The repetition rate of the Q-switched pulse was observed to increase with the pump power as shown in Fig. 6, according to which the repetition rate increased from 128 to 278 kHz, whereas the pump power

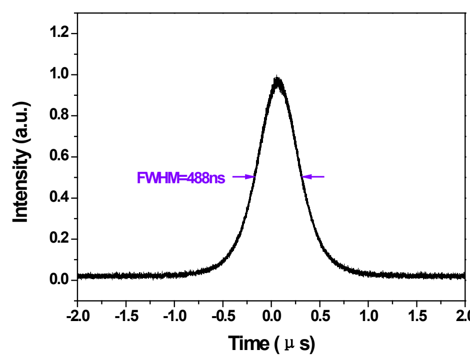

Fig. 5. The pulse width at the pump power of 600 mW.

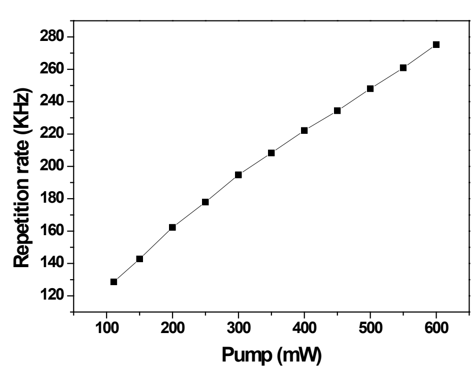

Fig. 6. Pulse repetition rate increased with the pump power.

increased from 110.9 to 600 mW, which means that we can tune the repetition rate by controlling the pump power, so as to reach the needs for different pulse repetition rates. The pulse widths decreased from 1.92 μs to 488 ns as shown in Fig. 7. High single-pulse energy of 47 nJ was realized under the pump power of 600 mW. As the SWCNT was placed on the surface of the fiber cladding, the fiber laser could operate a long-time stable Q-switched laser.

In conclusion, we prepare a SA with SWCNT using a special chemical-corrosion method. Then, we build an Er-doped all-fiber laser and introduce the SA into the fiber laser. The fiber laser is successfully Q-switched above definite pump power. The maximum output power is 13.1 mW. By increasing the pump power, the repetition rate of the pulse is tuned from 128 to 278 kHz continuously and the pulse width is shortened from 1.92 μs to 488 ns, which benefits the needs for different pulse repetition rates. As the SWCNT is placed on the surface of the fiber cladding instead of inserting cavity exempt from high energy of the laser in fiber core, it results in a long-time stable Q-switching operation without the thermal injury. The modulation method for Q-switching by evanescent field is a promising method for high-power pulsed fiber lasers.

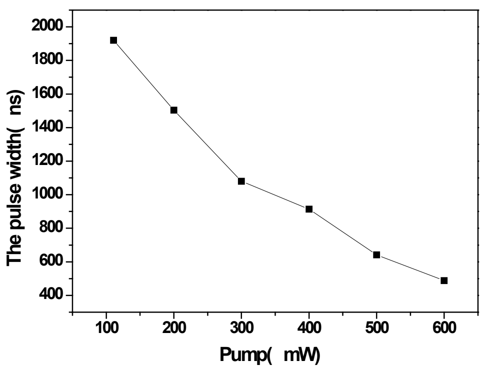

Fig. 7. The pulse width versus pump power.

This work was supported by the National Natural Science Foundation of China (No. 61177047) and the Key Program of the National Natural Science Foundation of China (No. 61235010).

References

1. L. Luo and P. L. Chu, Opt. Commun. **161,** 257 (1999).
2. N. A. Russo, R. Duchowicz, J. Mora, J. L. Cruz, and M. V. Andres, Opt. Commun. **210,** 361 (2002).
3. P. Roy, D. Pagnoux, L. Mouneu, and T. Midavaine, Electron. Lett. **33,** 1317 (1997).
4. H. H. Kee, G. P. Lees, and T. P. Newson, Electron. Lett. **34,** 1318 (1998)
5. J. H. Yim, W. B. Cho, S. Lee, Y. H. Ahn, K. Kim, H. Lim, G. Steinmeyer, V. Petrov, U. Griebner, and F. Rotermund, Appl. Phys. Lett. **93,** 161106 (2008).
6. Y. C. Chen, N. R. Raravikar, L. S. Schadler, P. M. Ajayan, Y. P. Zhao, T. M. Lu, G. C. Wang, and X. C. Zhang, Appl. Phys. Lett. **81,** 975 (2002).
7. S. Kivistö, T. Hakulinen, A. Kaskela, B. Aitchison, D. P. Brown, A. G. Nasibulin, E. I. Kauppinen, A. Härkönen, and O. G. Okhotnikov, Opt. Express **17,** 2358 (2009).
8. Z. Sun, T. Hasan, F. Wang, A. G. Rozhin, I. H. White, and A. C. Ferrari, Nano Res. **3,** 404 (2010).
9. J. H. Im, S. Y. Choi, and F. Rotermund, Opt. Express **18,** 18264 (2010).
10. X. M. Liu, D. D. Han, Z. P. Sun, C. Zeng, H. Lu, D. Mao, Y. D. Cui, and F. Q. Wang, Sci. Rep. **3,** 2718 (2013).