

Passively Q -switched Tm-doped fiber lasers with carbon nanotubes

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We demonstrate a passively Q -switched Tm-doped fiber laser with carbon nanotubes (CNTs), yielding a maximum output average power of around 82 mW and the corresponding pulse energy of 1.2 μ J. The laser operates at ~ 1.985 μ m with repetition rates ranging from 26 to 69 kHz and pulse-duration from 1.5 to 2.6 μ s. Our proposed laser shows that the CNTs are promising for the potential Q -switched Tm-doped fiber laser with high energy and tunable wavelength operation. To the best of our knowledge, this is the first report of a Q -switched Tm-doped fiber laser with CNTs as saturable absorber.

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Q -switched fiber lasers with large pulse energy are very attractive for applications such as medical treatment, micromachining, diagnostics, and others. Due to the well-known broad fluorescence spectrum and cross-relaxation process, Tm-doped fiber (TDF) lasers enjoy potential tunable operation and high quantum efficiency. In the past years, actively Q -switched TDF lasers with large pulse energy have been produced by employing active modulations^[1–8]. On the other hand, passively Q -switched fiber lasers are of special interests due to a more compact geometry, simpler setup, and more tunable operation^[9,10] than actively Q -switched lasers, which usually require additional switching electronics. Passively Q -switched TDF lasers with large pulse energy, short pulse duration, and relatively high repetition rate have been successfully generated by using semiconductor saturable mirror (SESAM)^[11–13].

Recently, carbon nanotubes (CNTs) have realized a novel paradigm of the passive saturable absorber (SA) with the advantages of dimension minimized, wide operating bandwidth, simple manufacturing process, and high nonlinearities. Based on the CNTs, stable Q -switched Er-doped fiber lasers have been reported, resulting in output average power of 130 μ W and 3.27 dBm (~ 3 mW), respectively^[14,15]. However, the average output power and pulse energy were seriously limited by the thermal damage of the fragile nanotubes induced by the high peak-power of Q -switched pulses. More recently, Liu *et al.* firstly reported a 2- μ m Q -switched mode-locked Tm³⁺:YAP laser with CNTs in a compact Z-type cavity^[16].

In this letter, we demonstrate a Q -switched TDF laser with average output power of up to 82 mW, pulse energy of 1.2 μ J, and center wavelength of 1985 nm by CNTs-SA. To the best of our knowledge, this is the first report of a Q -switched TDF laser with CNTs-SA.

Laser scheme is shown in Fig. 1. The laser system had

a cavity of sigma configuration, formed by a CNTs-SA, a pump combiner, a piece of double-cladding Tm-doped silica fiber, a polarization beam splitter (PBS), and wave plates. The CNTs-SA was sandwiched between two flat mirrors (one with a high transmission (HT) and the other with high reflection (HR) at 2 μ m) to isolate from the air to avoid the thermal damage. Figure 2 (red line) presents the low intensity reflectance spectrum of the CNTs measured by an ultraviolet (UV)-visible-near-infrared (NIR) spectrophotometer (Lambda 950, PerkinElmer Company). The spectrum exhibits a broad absorption band extending from 1.75 to 2.05 μ m. The TDF had a core/cladding diameter of 10.3/125 μ m and corresponding numerical apertures (NAs) of 0.15/0.46, respectively. The nominal pump absorption was 3 dB/m at 792 nm, and hence an active fiber length of ~ 2 m was chosen to ensure efficient pump absorption and relatively low reabsorption at the lasing wavelength. The pump source was a laser diode (LD) with 0.22 NA and 105/125 μ m fiber pigtail, and a multimode pump combiner was used to deliver pump light into the

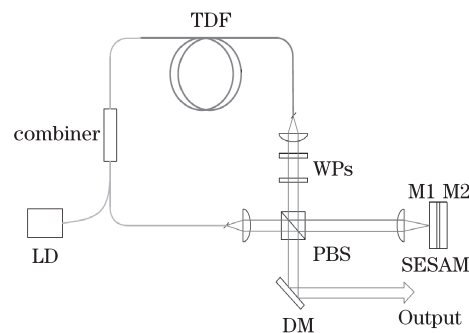


Fig. 1. Schematic of Tm-doped fiber laser. WPs, half-/quarter-wave-plates; M1, flat mirror, HT; M2, flat mirror, HR DC, dichroic mirror (HR 2000 nm/AR 793 nm).

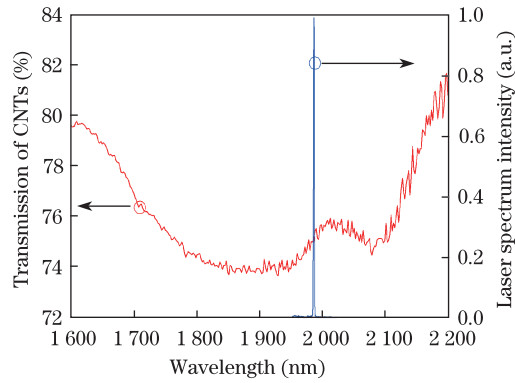


Fig. 2. (Color online) Spectrum of CNTs and Q -switched laser.

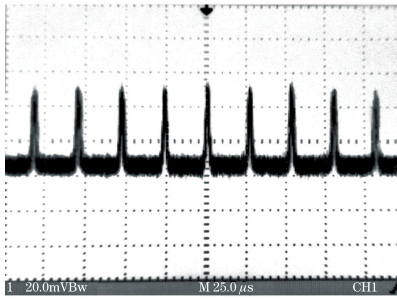


Fig. 3. Typical Q -switched pulse trace at 38 kHz.

inner-cladding of TDF. A 2-m-long nominal Tm-fiber-matched passive fiber pigtail (10/125 μm , 0.15/0.46) of combiner was fusion spliced to the active fiber and all fiber ends were angle cleaved to eliminate back reflection. A PBS combined with half and quarter wave plates were employed to control the output ratio of laser power. Two lens with identical focal length ($f=40$ mm) were used to collimate the beam in the cavity. The beam incident on the CNTs-SA was focused by a third lens with the focal length of 30 mm.

When the pump voltage was increased to 1.78 V the instable Q -switching operation occurred. Stable Q -switched pulses were obtained by tuning the wave plates, yielding the output average power of 14 mW, the repetition rate of 26 kHz, and pulse width of 2.6 μs . Figure 3 presents a typical stable Q -switched pulse trace and the corresponding spectrum at 38 kHz is shown in Fig. 2 (blue line). The spectrum was analyzed using a 0.55-m monochromator containing a 300-lines/mm grating blazed at 1800 nm and a TE-cooled InGaAs detector (0.8–2.2 μm), and the resolution of the monochromator was estimated to be ~ 0.9 nm at 2 μm . As can be seen, our Q -switched laser operated at the centre wavelength of 1985 nm with the full-width at half-maximum (FWHM) of 2 nm.

As shown in Fig. 4, the output average power and repetition rate monotonically increase with the further increase of pump voltage. At the pump voltage of 2.32 V, the maximum output average power of 82 mW was obtained, corresponding to the maximum repetition rate of 69 kHz. Figure 5 shows the pulse energy and duration as a function of the pump voltage. With the increase of the pump voltage, the pulse energy almost linearly grows and the pulse width decreases, which is different from the

theoretical predictions (pulse energy and width are constant and independent of pump power)^[9]. We attribute the discrepancy to the larger energy storage and greater energy extraction efficiency by the long fiber length and relatively weak pump intensity^[13]. The maximum pulse energy was calculated to be 1.2 μJ at the average output power of 82 mW.

Pulse duration was measured by high-speed oscilloscope (300-MHz bandwidth, 35-ps detector) and it decreased with the increasing pump voltage. Figure 6 shows the pulse duration with the output average power of 82 mW. The pulse duration (FWHM) was measured to be ~ 1.5 μs and the pulse shared a symmetric Gaussian-shape rather than the predicted sech^2 -shape^[9]. In fact, similar pulse-shape had also been reported by Herda *et al.*^[11]. We expect the pulse duration can be shorted down to ns-levels by using a shorter-length fiber combined with core pump scheme or increasing available pump intensity according to the theoretical predications^[9].

The high average output power and large pulse energy we obtained were scaled a lot than previous results^[14,15]. We attributed this to the improvement of thermal durability of CNTs. Due to the broad absorption bandwidth of CNTs in the wavelength range of 2 μm , our proposed laser is promising in constructing a tunable Q -switched laser by employing a diffraction grating or changing fiber length in a linear-cavity.

In conclusion, we report a Q -switched TDF laser with the maximum average output power of 82 mW and the corresponding pulse energy of 1.2 μJ by employing CNTs-SA. The laser operates at around 1.985 μm ,

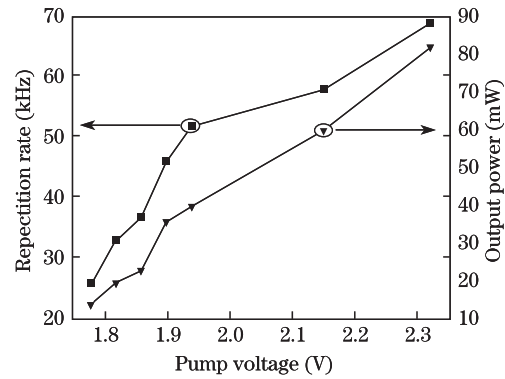


Fig. 4. Pulse repetition rate and average output power as functions of the pump voltage.

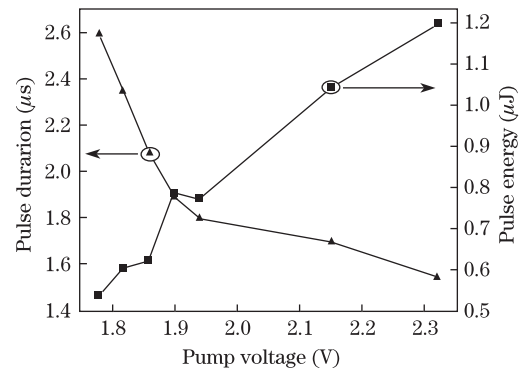


Fig. 5. Pulse duration and energy as functions of the pump voltage.

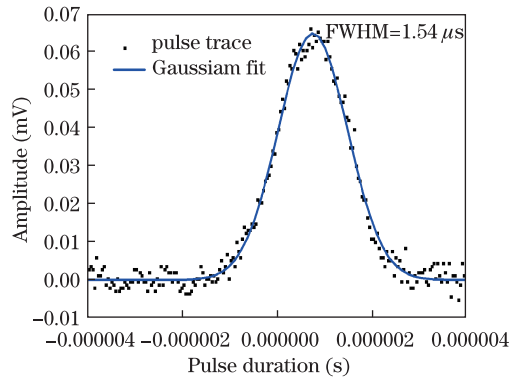


Fig. 6. Measured pulse width with output average power of 82 mW.

with pulse-repetition-rate ranging from 26 to 69 kHz and pulse-duration from 1.5 to 2.6 μs . Our proposed laser shows that the CNTs are promising for the Q -switched TDF laser with extremely high energy and tunable wavelength operation due to the improved thermal durability and large bandwidth of CNTs. To the best of our knowledge, this is the first demonstration of a Q -switched TDF laser with CNTs, which is of great importance for LIDARs.

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References

1. A. F. El-Sherif and T. A. King, *Opt. Lett.* **28**, 22 (2003).

2. M. Eichhorn, *Opt. Lett.* **32**, 1056 (2007).
3. J.-H. Geng, Q. Wang, J. Smith, T. Luo, F. Amzajerdian, and S.-B. Jiang, *Opt. Lett.* **36**, 2293 (2011).
4. W. Shi, E. B. Petersen, D. T. Nguyen, Z.-D. Yao, A. Chavez-Pirson, N. Peyghambarian, and J.-R. Yu, *Opt. Lett.* **36**, 3575 (2011).
5. M. Eichhorn and S. D. Jackson, in *Proceedings of Conference on Lasers and Electrooptics/QELS CFD7* (2008).
6. T. Yu, S. Shu, and W. Chen, *Chin. Opt. Lett.* **9**, 041407 (2011).
7. R. Zhou, Y. Ju, Y. Zhang, and Y. Wang, *Chin. Opt. Lett.* **9**, 071401 (2011).
8. J.-Q. Xu, L. Xu, and Y.-L. Tang, in *Proceedings of Conference on Lasers and Electro-Optics/QELS JTuD67* (2010).
9. G. J. Spühler, R. Paschotta, R. Fluck, B. Braun, M. Moser, G. Zhang, E. Gini, and U. Keller, *J. Opt. Soc. Am. B* **16**, 376 (1999).
10. T. Hakulinen and O. G. Okhotnikov, *Opt. Lett.* **32**, 2677 (2007).
11. R. Herda, S. Kivistö, and O. G. Okhotnikov, *Opt. Lett.* **33**, 1011 (2008).
12. S. Kivistö, R. Koskinen, J. Pajaste, S. D. Jackson, M. Guina, and O. G. Okhotnikov, *Opt. Express* **16**, 22058 (2008).
13. J.-Y. Long, D.-Y. Shen, Y.-S. Wang, W. Zhao, Y. An, and W. Zhou, *Laser. Phys.* **22**, 986 (2012).
14. B. Dong, J.-Z. Hao, J.-H. Hub, and C.-Y. Liaw, *Opt. Fiber Technol.* **17**, 105 (2011).
15. Y. W. Song, *Appl. Opt.* **51**, 292 (2012).
16. J. Liu, Y.-G. Wang, Z.-S. Qua, and X.-W. Fan, *Opt. Laser Technol.* **44**, 960 (2012).