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All-fiber ultrafast thulium-doped fiber ring laser with dissipative soliton and noise-like output in normal dispersion by single-wall carbon nanotubes

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An ultrafast thulium-doped fiber laser with large net normal dispersion has been developed to produce dissipative soliton and noise-like outputs at 1.9 μm. The mode-locked operation was enabled by using single-wall carbon nanotubes as saturable absorber for all-fiber configuration. Dissipative soliton in normal dispersion produced by the fiber laser oscillator was centered at 1947 nm with 4.1-nm FWHM bandwidth and 0.45 nJ/pulse. The output dissipative soliton pulses were compressed to 2.3 ps outside the laser cavity. © *2013 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4813108]

Thulium-doped fiber (TDF) laser operating around "eye-safe" wavelength range of 1.9 μm have gained intense interests recently due to its significant applications in medicine, remote sensing, optical coherence tomography, nonlinear mid-IR generation, and others. Many of these laser applications require high-intensity and high-energy pulse output. This can be achieved by mode-lock fiber lasers. The first passively mode-locked Tm-doped fiber laser was reported by Nelson *et al.*[1] It was operated under soliton regime by nonlinear polarization evolution (NPE). This was followed by many recent works since 2008 when fiber optical components become available at this wavelength. Noise-like (NL) pulses were also reported recently based on this mechanism in an all-fiber configuration.[2]

Early mode-locked fiber lasers were operated in soliton regime. Peak pulse energy of fiber lasers were limited by the nonlinearity of construction fibers. More recently, by implementing normal-dispersion fiber cavity, fiber lasers operated in dissipative soliton regimes have also been demonstrated. In contrast to conservative solitons, dissipative solitons produced from normal-dispersion lasers have demonstrated much higher pulse energy by allowing strongly chirped pulses to circulate in the oscillator, which suppresses the side effects from the intra-cavity nonlinearity that tends to destabilize and break down pulses.[3] Gumenyuk reported a mode-locked TDF laser with net normal dispersion in the cavity.[4] This was achieved by introducing a highly chirped fiber Bragg grating at 2 μm into the fiber cavity. The mode-locked operation was realized using a wavelength-specific semiconductor saturable absorber mirror (SESAM). Haxsen *et al.* also reported a hybrid mode-locked fiber configuration by a combination of SESAM and NPE mechanisms for which normal dispersion fiber (NDF) was used to create net normal intra-cavity dispersion.[5]

Another effective technique to achieve the mode-locked operation is to use nanomaterial-enabled SAs. Recently, single-wall carbon nanotubes (SWCNTs) and graphene have been implemented as SA elements for ultrafast fiber laser development.[6–8] Both SWCNTs and graphene exhibit wide saturable absorption bandwidth, which makes them uniquely suitable for mid-IR ultrafast photonics applications at 2 μm and beyond.[9] Particularly, recent studies also reveal that SWCNTs has higher optical damage threshold than some other SAs.[10] This trait makes SWCNTs an excellent candidate for ultrafast fiber laser with high pulse energy. SWCNTs based SAs have been reported to successfully generate dissipative solitons for 1-μm and 1.5-μm fiber lasers, respectively.[6,11,12]

In this letter, we demonstrate a 1.9-μm passively mode-locked TDF ring oscillator with large net normal dispersion to produce both dissipative soliton and noise-like outputs. The mode-locked operation was enabled by using optically deposited SWCNTs on the fiber end tip as the saturable absorber. Dissipative soliton produced from all-fiber dispersion-managed mode-locked TDF ring oscillator was centered at 1947 nm with 4.1-nm FWHM bandwidth in normal dispersion.

Since most of silica fibers have anomalous dispersion around 1.9 μm, carefully selected segments of specialty fiber with normal dispersion were added to the cavity to over compensate the anomalous dispersion from other fibers and create large net normal dispersion in the cavity at 1.9 μm. The dispersion of single-mode fiber can be considered as the sum of material's dispersion and waveguide's dispersion, for which the waveguide's dispersion is determined by the fiber's geometry and refractive index profile. By reducing the core diameter and increasing numerical aperture (NA), the zero dispersion wavelength of the fiber can be pushed towards the longer wavelength.[13] The core diameter of NDF we used is 2.2 μm and the NA is 0.35 (Nufern UHNA4). A white-light interferometry technique[14] was developed to measure the fiber's dispersion, for which Tm-doped fiber spontaneous emission is used as the light source. Figure 1 shows the measured interference pattern and the fitting results. The dispersion of the normal-dispersion fiber is measured to be 93 ps^2/km at 1.9 μm. Using the same method, the anomalous dispersion of the SMF-28e fiber at 1.9 μm was measured to be -67 ps^2/km. The dispersion of the Tm-doped active fiber used in the experiment was estimated to be -12 ps^2/km.

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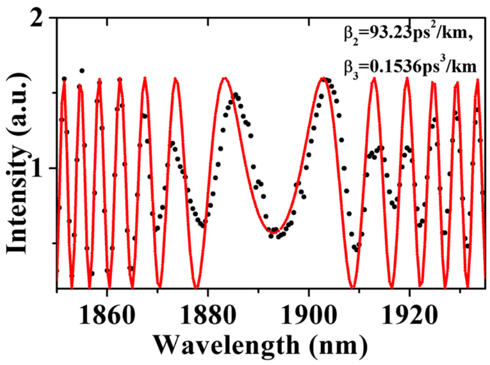

FIG. 1. White light interference fringe for NDF dispersion measurement and the fitting curve (red).

The method used to fabricate our SWCNTs SAs is described as follows. 0.2 mg/ml SWCNTs (Sigma-Aldrich) solution was developed by dispersing into N-dimethylformamide solvent and ultrasonically bathed for 2 h at room temperature. The dispersed SWCNTs were then optically deposited onto the end tip of angle-cut single mode fiber by an optical trapping method described in Ref. 15. In this approach, a 100-mW 1550-nm Er-doped fiber amplified spontaneous light source was used to optically trap SWCNTs onto the fiber tip. An enhanced back-reflection can be registered by an optical spectrum analyzer when the SWCNTs were deposited. The SWCNTs end-coated fiber was then connected with a fiber patch cord using a bare fiber connector and a mating sleeve and thus completed the SWCNTs SA fabrication.

The fabricated SWCNTs SA is inserted into an all-fiber ring cavity as illustrated in Figure 2. The active fiber is 100-cm long single mode Tm-doped silica fiber with 5-μm core diameter and 0.23 NA. Two 1550-nm/1900-nm wavelength division multiplexing (WDM) couplers are used to couple pump light into the cavity. The amplified spontaneous emission from an erbium-doped fiber amplifiers fusion spliced to WDM provides forward and backward pumping simultaneously. A polarization insensitive isolator with 10% insertion loss and over 35-dB isolation at 2-μm wavelength is fusion spliced into the cavity and thus enforces a counterclockwise unidirectional ring. Part of the intra-cavity energy is coupled out through a 3-dB output coupler. 1% of the output is picked by a fast detector (EOTECH ET-5010F) for oscilloscope and radio-frequency (RF) analysis. Another isolator for 2-μm wavelength is also fusion spliced to output port to suppress back reflection into the cavity. An in-line polarization controller (PC) is included to finely tune the intra-cavity polarization state as for the consideration to balance the intrinsic weak birefringence of the included single mode fibers. No extra optical filter is added into the ring cavity. The spectral filtering required for pulse stabilization is majorly provided simultaneously with the temporal filtering at the fabricated SWCNTs SA. The Tm-doped fiber itself also provides spectral filtering but is considered as a minor factor because of the relatively narrow spectral bandwidth of the mode-locked output. In total, there is about 6 m of SMF-28e pigtail fiber in the laser cavity. The length of the NDF included in the cavity is 22 m. The net dispersion in the cavity is calculated as 1.63 ps^2. The small amount of dispersion due to the optical isolator is neglected.

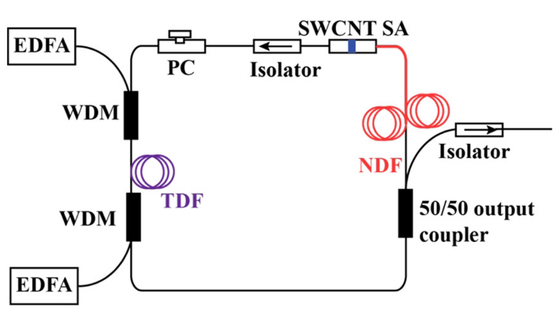

FIG. 2. Scheme of the TDF ring cavity, based on fabricated SWCNTs SA.

Mode-locked operation is self-started as the pump ramps up to 650 mW. An output spectrum shown in Figure 3(a) reveals a FWHM bandwidth of 5.1-nm laser pulse output. Figure 3(b) shows pulse trains produced by the fiber oscillator measured by an oscilloscope. The pulse width determined by a custom-built intensity autocorrelator is shown in Figure 3(c). Up conversion signal from a long scanning range of over 500 ps reveals a coherence spike on the zero time-delay over a wide pedestal. This indicates that the laser operates under the NL regime.[16,17] Results shown in Figure 3(c) suggest that a bunch of ultra-short pulses with randomly varying pulse width and peak power are generated within an envelope of over 300 ps. Figure 3(d) is the RF spectrum (measured by Agilent E4411B) of the NL pulses at the fundamental repetition rate; two wide side lobes and low signal to noise (SNR) are indicative of the inherent jittering of NL operation. The output power was measured as 8.5 mW, which corresponds to 1.27-nJ per noise like pulse bundle. It is also confirmed that the NL pulses produced by the laser cavity cannot be compressed by propagating through negative dispersion compensating media.

By reducing the pump power down to 605 mW, stable CW mode-locked pulses with significantly different characteristics were also observed. Figure 4(a) shows a typical optical spectrum of the stable mode-locked output with a resolution of 0.1 nm on a linear scale. "Cat-ear" like spectrum with steep rising and falling edges is observed, which is indicative of the dissipative soliton operation in normal dispersion of the laser.[3] The central wavelength locates at 1947 nm and the 3-dB spectral width is about 4.1 nm. Figure 4(b)

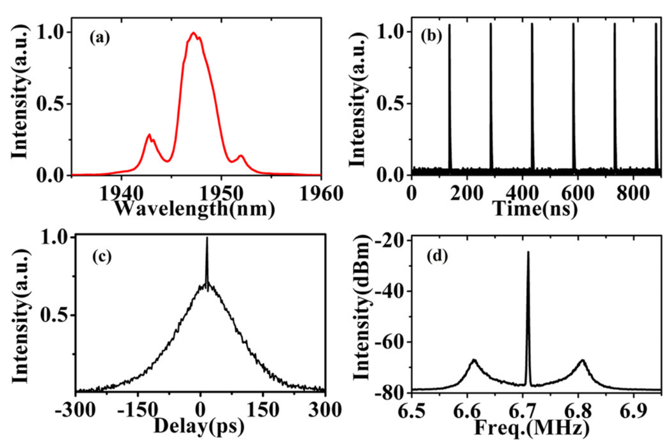

FIG. 3. Fiber laser under noise-like operation: (a) spectrum; (b) pulse train on oscilloscope; (c) intensity autocorrelation; (d) RF spectrum.

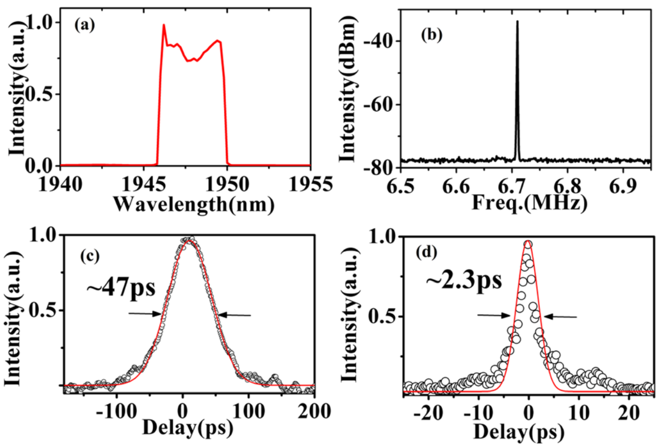

FIG. 4. Dissipative soliton operation: (a) spectrum; (b) RF spectrum; (c) autocorrelation of the original pulse and Gaussian fitting; (d) autocorrelation of the compressed pulse and Gaussian fitting.

is the RF spectrum of the dissipative soliton output at the fundamental repetition rate. The SNR is as high as 46 dB, this is comparable to Er-doped mode-lock fiber laser enabled by SWCNT.[15] It is indicative of stable operation and low jittering of the pulse trains. Figure 4(c) shows the autocorrelation trace of the produced pulses directly from the cavity. It indicates single pulse operation. The autocorrelation deconvolution factor retrieved from the spectrum [Figure 4(a)] is close to 1.4. Assuming a Gaussian profile, it yields a pulse duration of 47 ps. Combined with the 4.1-nm bandwidth, the time-bandwidth product (TBP) is calculated as 15.21. This is over 30 times of the transform limit 0.44, which suggests that the pulse is strongly chirped. The RF spectrum shown in Figure 4(b) also confirms only one pulse is generated per round trip. Figure 4(d) shows the pulses compression after propagating 180-m SMF-28e fiber outside the cavity. The chirped pulses are compressed to 2.3 ps, which are close to the 1.4-ps Fourier limit. The average output power from the 50% output port is measured as 3 mW under 605-mW pump. Given 6.71-MHz repetition rate, the per-pulse energy is about 0.45 nJ for the dissipative soliton pulses in normal dispersion. This value is about 4 times greater than that of the soliton pulse enabled by SWCNTs SA in a ring configuration.[11] The anomalous dispersion exhibited from the gain fiber is considered as the major factor to limit the dissipative pulse energy as the pulse trends to evolve into solitons during amplification. The stability of the fiber laser was also tested. The fiber laser is capable of several hours' continuous operation under both mode-locked regimes. We intermittently tested the laser over a period of 2 months, and consistent operational performance has also been confirmed.

In summary, an all-fiber mode-locked Tm-doped laser ring oscillator with large normal intra-cavity dispersion is demonstrated in this paper. The SWCNT SA fabricated by the optical deposition method was used to achieve pulse output. Normal-dispersion fibers were introduced to create a net normal dispersion ring cavity to produce dissipative soliton outputs. The laser is pumped by the amplified spontaneous emission source at 1.55 μm; both noise-like and dissipative soliton operation regimes were achieved around 1947 nm by changing the pump power. Self-started under 650-mW pump, noise-like pulse energy of 1.27-nJ per NL pulse bundle, and over 100-ps wide envelope were produced. The dissipative soliton output was achieved under lowered 605-mW pump; heavily chirped pulses of 47 ps with 4.1-nm FWHM bandwidth were observed. The dissipative soliton pulses at 1947 nm were compressed to 2.3 ps outside the laser cavity.

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[1] L. E. Nelson, E. P. Ippen, and H. A. Haus, Appl. Phys. Lett. **67**, 19 (1995).
[2] Q. Wang, T. Chen, B. Zhang, A. P. Heberle, and K. P. Chen, Opt. Lett. **36**, 3750 (2011).
[3] W. H. Renninger, A. Chong, and F. W. Wise, Phys. Rev. A **77**, 023814 (2008).
[4] R. Gumenyuk, I. Vartiainen, H. Tuovinen, and O. G. Okhotnikov, Opt. Lett. **36**, 609 (2011).
[5] F. Haxsen, D. Wandt, U. Morgner, J. Neumann, and D. Kracht, Opt. Lett. **37**, 1014 (2012).
[6] Z. Sun, A. G. Rozhin, F. Wang, T. Hasan, D. Popa, W. O'Neill, and A. C. Ferrari, Appl. Phys. Lett. **95**, 253102 (2009).
[7] K. Kieu and F. Wise, IEEE Photonics Technol. Lett. **21**, 128 (2009).
[8] M. Zhang, E. J. R. Kelleher, F. Torrisi, Z. Sun, T. Hasan, D. Popa, F. Wang, A. C. Ferrari, S. V. Popov, and J. R. Taylor, Opt. Express **20**, 25077 (2012).
[9] Z. Sun, T. Hasan, and A. Ferrari, Physica E **44**, 1082 (2012).
[10] S. Set, H. Yaguchi, Y. Tanaka, and M. Jablonski, J. Lightwave Technol. **22**, 51 (2004).
[11] M. A. Solodyankin, E. D. Obraztsova, A. S. Lobach, A. I. Chernov, A. V. Tausenev, V. I. Konov, and E. M. Dianov, Opt. Lett. **33**, 1336 (2008).
[12] K. Kieu and F. W. Wise, Opt. Express **16**, 11453 (2008).
[13] B. Ainslie and C. Day, J. Lightwave Technol. **4**, 967 (1986).
[14] Q. Ye, C. Xu, X. Liu, W. H. Knox, M. F. Yan, R. S. Windeler, and B. Eggleton, Appl. Opt. **41**, 4467 (2002).
[15] A. Martinez, K. Fuse, B. Xu, and S. Yamashita, Opt. Express **18**, 23054 (2010).
[16] L. Wang, X. Liu, Y. Gong, D. Mao, and L. Duan, Opt. Express **19**, 7616 (2011).
[17] M. Horowitz, Y. Barad, and Y. Silberberg, Opt. Lett. **22**, 799 (1997).