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Sub-200 femtosecond dispersion-managed soliton ytterbium-doped fiber laser based on carbon nanotubes saturable absorber

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Abstract: Ultrafast fiber laser light sources attract enormous interest due to the booming applications they are enabling, including long-distance communication, optical metrology, detecting technology of infra-biophotons, and novel material processing. In this paper, we demonstrate 175 fs dispersion-managed soliton (DMS) mode-locked ytterbium-doped fiber (YDF) laser based on single-walled carbon nanotubes (SWCNTs) saturable absorber (SA). The output DMSs have been achieved with repetition rate of 21.2 MHz, center wavelength of 1025.5 nm, and a spectral width of 32.7 nm. The operation directly pulse duration of 300 fs for generated pulse is the reported shortest pulse width for broadband SA based YDF lasers. By using an external grating-based compressor, the pulse duration could be compressed down to 175 fs. To the best of our knowledge, it is the shortest pulse duration obtained directly from YDF laser based on broadband SAs. In this paper, SWCNTs-SA has been utilized as the key optical component (mode locker) and the grating pair providing negative dispersion acts as the dispersion controller.

OCIS codes: (320.7090) Ultrafast lasers; (140.4050) Mode-locked lasers; (140.3510) Lasers, fiber.

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1. Introduction

Ultrafast fiber lasers have received considerable attention due to their various advantages such as compactness, robustness, and good spatial mode quality. Several kinds of mode-locking techniques for pulse lasers have been proposed to meet the demands of many applications in long-distance communication, optical metrology, detecting technology of infra-biophotons, and novel material processing. In recent years, a variety of saturable absorbers(SAs) (e.g. carbon nanotubes (CNTs) [1–12], Graphene [12–21], topological insulators (TI) [22–28], black phosphorus (BP) [29, 30], and transition-metal dichalcogenides (TMDs) [31–52]) have been intensively investigated for ultrashort pulse generation. Among them, CNTs has been considered as a promising kind of material for SAs for its economic efficiency, convenient fabrication procedure, short recovery time, high damage threshold and broad absorption bandwidth.

The pursuit of ultrashort laser pulses at various wavelengths has long been in subject for scientists. Thus far, fiber lasers continue to lag significantly behind the solid-state lasers in pulse duration. Up to date, a number of researchers have focused on the generation of

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ultrashort pulses from fiber lasers operating 1 μm, 1.5 μm and 2.0 μm with different types of low-dimensional materials SAs. Here in Fig. 1, we classify the existing mode-locked fiber lasers based on low-dimensional materials SAs in terms of emission wavelength and pulse duration of laser sources. Despite of various advantages, only several kinds of mode-locked fibers lasers were realized. In 2-μm regime, thulium-doped and holmium-doped fiber lasers based on different low-dimensional materials SAs were reported. In 1.5-μm regime, erbium -doped fiber lasers are no doubt the most widely employed. For 1-μm regime, YDF laser with various types of SA were realized in recent years. However, most of them were limited to picosecond level pulse duration. Contrary to the results of lasers achieved in the 1.5 μm and 2 μm spectral regions, the pulse duration of 1.0 μm fiber lasers is still too longer.

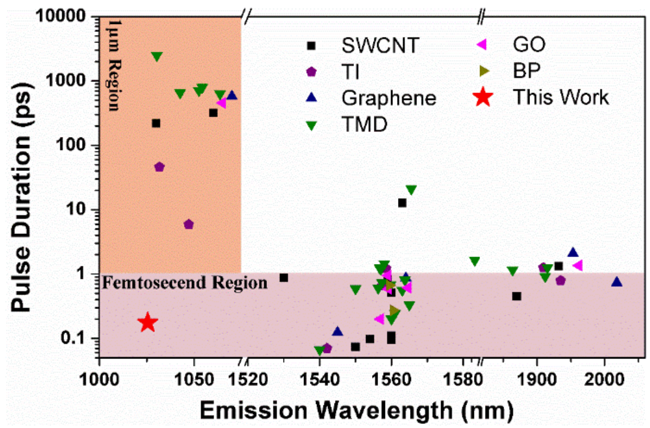

Fig. 1. Fiber lasers based on different low-dimensional materials SAs classified in terms of emission wavelength and pulse duration [1–52].

YDFs are promising gain sources for ultrafast laser sources at 1 μm. The high quantum efficiency, a long upper-state life time, absence of ground-state absorption and excited-state absorption by YDFs make them very attractive to produce short, high peak power pulses. In order to improve the performance of ultrafast fiber lasers, DMSs fibers lasers have been explored. To obtain dispersion-managed regime where a wider bandwidth is produced and lower nonlinearity effect, control of the net dispersion in fiber laser cavity is required. However, achieving a negative cavity GVD is challenging for YDF lasers since it is difficult to find a fiber has anomalous GVD at 1 μm to compensate the normal GVD of the gain fiber and single-mode fiber (Corning HI1060) in the laser.

In this paper, we report an YDF mode locked laser based on SWCNTs SA, which can generate 175 femtosecond laser pulses. To the best of our knowledge, it is shortest mode-locked pulse duration obtained in 1.0 μm regime by utilizing broadband materials SAs as the mode lockers and we demonstrate that DMS can be generated from YDF fiber laser using SAs for the first time. Stable mode-locked laser pulse trains can be obtained after two output terminals with different pump power (from 50 mW to 150 mW). The spectrum of output is relative wide that the full width half maximum (FWHM) is 32.7 nm central in the 1025.5 nm. The repetition frequency is 21.2 MHz and the total length of cavity is about 9.33 m.

2. Experimental setup

The schematic diagram of the dispersion-managed fiber laser, which incorporates SWCNT SAs in the cavity, is shown in the Fig. 2(a). The ring cavity includes a wavelength division multiplexer (WDM), a gain fiber, two output couplers (20/80 OC1, 10/90 OC2), two collimators (Col1, Col2), two 1000 line/mm transmission grating pairs (GP1, GP2) (LightSmyth Technologies, LSFSG-1000-3212-94), a polarization-independent isolator (PI-ISO), a polarization controller (PC), SWCNT-based SA, and four high reflective mirrors. The

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SWCNT-based SA is inserted between the PC and WDM. The SWCNT powder was synthesized by the electric arc discharge technique. The diameter of the SWCNTs was 1.5 nm and the thickness of the composite absorber was about 10 μm. SWCNT/polyvinyl alcohol (PVA) film was prepared in polystyrene cell by the vertical evaporate method. And then we fabricated SWCNT with the wall of the cell in the experiment. The detailed information of SWCNT process was given previously in [5]. Figure 2(b) shows the measured nonlinear saturable absorption curve. In our experiment, the SWCNT-based SA shows nonlinear properties with the modulation depth, nonsaturable loss, and saturable intensity of 52.7%, 51% and 2.512 MW/cm^2, respectively. The setup is based on a home-made picosecond YDF laser (Repetition rate: 24.63 MHz and Pulse width: 5.75 ps). The 0.4 m active YDF (Coractive) is core-pumped via laser diode at 976 nm through 980/1030 WDM. The YDF has absorption coefficient of 125 dB/m at 915 nm and group velocity dispersion (GVD) of 23 ps^2/km. All the passive components are made by single mode fibers (SMF, HI1060) with GVD of 23 ps^2/km at 1030 nm. The total cavity length of ring cavity is around 9.33 m. The fiber section is about 8.93 m (SMF: ~8.53 m and YDF: ~0.4 m), and the corresponding dispersion of fiber section is approximately 0.205 ps^2. In order to control the net cavity dispersion, we purposely incorporated a GP1 (distance 34.21 mm) into the laser cavity. In addition, GP2 is used outside the cavity for compressing the output DMSs. The GP1 provides –0.152 ps^2 into the cavity and the total net dispersion in cavity has been calculated as 0.053 ps^2. In the next, the dispersion of output part (SMF) is 0.041ps^2 and GP2 introduces –0.107 ps^2. All of transmission gratings have the same parameters. The line density of them is 1000 Lines/mm and the angle of incidence is 31.3°. The wavelength range is 1030 ± 20 nm. The diffraction efficiency is large than 94% and the efficiency of different optimal polarization is equal. The output spectra are measured by the optical spectral analyzer (OSA, AQ 6370C, Yokogawa Inc.). And the pulse duration of DMS is detected by a commercial intensity autocorrelator (FR-103WS, Femtochrome Research Inc.). The pulse trains are monitored by a digital storage oscilloscope (20 GHz sampling scope, DSO9104A, Agilent Technologies Inc.) and radio frequency (RF) spectrum analyzer (N9000A, Keysight Inc.).

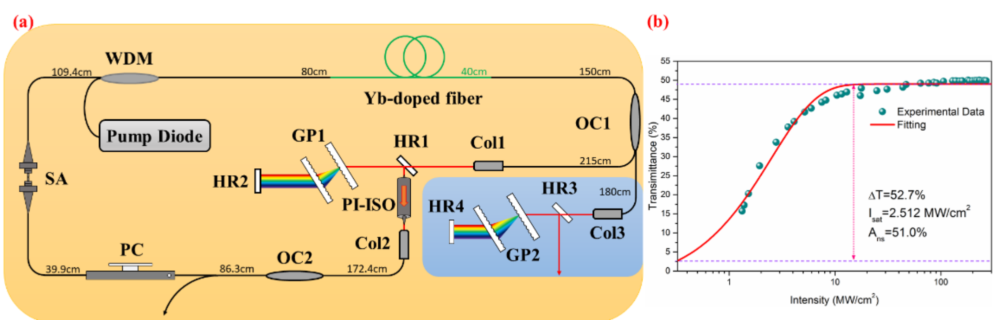

Fig. 2. (a) Schematic diagram of the dispersion-managed YDF laser by the SWCNT-based SA. WDM: wavelength division multiplexer; OC1, OC2: output couplers; Col1-Col3: collimators; GP1, GP2: grating pairs; HR1-HR4: high reflective mirrors; PI-ISO: polarization independent isolator; PC: polarization controller; SA: SWCNT-based SA. (b) Nonlinear transmission curve of the SWCNT-based SA.

3. Results and discussion

In this YDF fiber laser, continuous wave output is achieved at around 30 mW pump power. With appropriate PC setting, self-started mode locking of YDF laser occurred at the pump power of 50 mW. Once stable output pulses train is achieved by introducing an adjustment to the PC, no further PC disturbance is required and we could decrease the pump power to the mode-locking threshold for maintaining ultrafast pulses. Increasing the pump power more than 150 mW might possible damage the SWCNTs SA. For further confirmation, no mode-

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locking pulsed had been observed when SWCNTs SA was removed from the scheme during entire experiment. It can confirm that the SWCNTs SA is necessary for the entire mode locked procedure.

Figure 3 summarizes the mode-locking performance (OC1) of the YDF laser passively mode locked by the fiber-pigtailed SWCNT SA with a pump power of 70 mW. The output power from OC1 is 8.68 mW. Figure 3(a) illustrates a typical mode-locking optical spectrum, which has the full-width half-maximum of 32.7 nm and a central wavelength of 1025.5 nm. The responding Fourier-limited duration is 33.8 fs. Figure 3(b) shows a typical pulse train at repetition rate of 21.2 MHz, which agrees with the cavity length. The long range of temporal trace can confirm the pulse stability without Q-switching instability. The measured RF spectrum is shown in Fig. 3(c), which has a signal-to-noise ratio higher than 60 dB. The corresponding autocorrelation trace of the OC1 output pulses is plotted in the Fig. 3(d). By assuming sech^2 pulse profile, the pulsed duration is about 4.14 ps and the time bandwidth product (TBP) is 38.62.

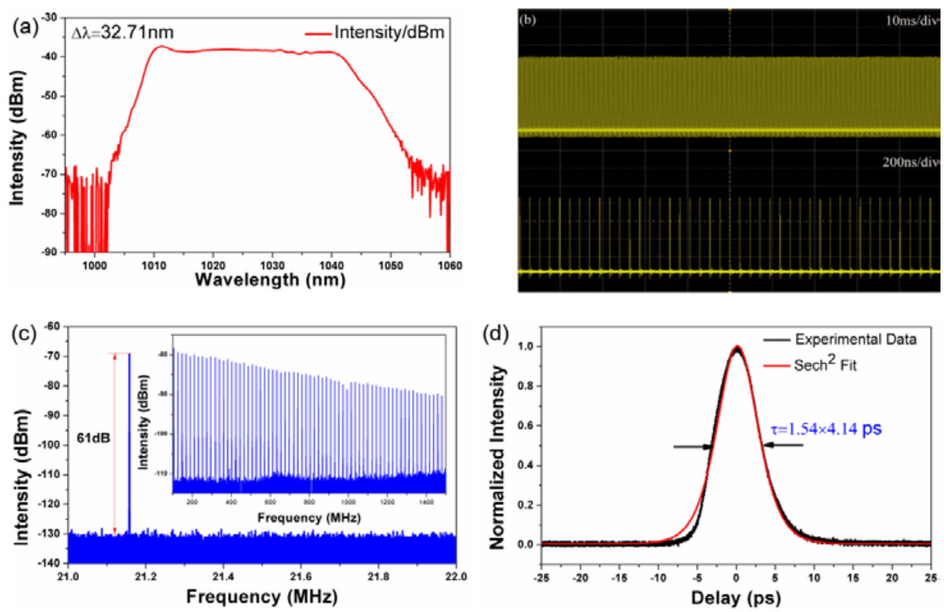

Fig. 3. Mode-locked pulse emission from the OC1 with a pump power of 70 mW. (a) The optical spectrum; (b) the typical pulse trains; (c) the corresponding RF spectrum at 21.16 MHz with a resolution bandwidth (RBW) of 1 Hz. Inset: RF spectrum at 21.16 MHz with RBW of 100 Hz; (d) the corresponding autocorrelation trace.

In order to investigate the characterization of OC2 under the same experimental condition as OC1, the optical spectrum, pulse train, the RF spectrum and autocorrelation trace of the mode-locked pulses are shown in Figs. 4(a)-4(d), respectively. The output power of OC2 is relative low that is under 1 mW. The optical spectrum is shown in Fig. 4(a). The central wavelength of the pulses is located at 1031.5 nm and the spectrum has a FWHM bandwidth of about 20.2 nm. The responding Fourier-limited duration is 55.3 fs. Comparing the Fig. 3(a) and the Fig. 4(a), it is not difficult to find that the profiles of the spectrums are almost entirely different although the experimental condition is same and the net dispersion is same too. The main reason of this probably is that the dispersion is not equal everywhere in the cavity. The cavity can be divided into two parts: one provides normal dispersion and the other provides completely different dispersion, which leads to a distribution of dispersion in the cavity. Figure 4(b) shows that the output train from OC2 is also remarkable and that the repetition rate is 21.2MHz has been proved. Similarly, the Fig. 4(c) proves that the fundamental repetition rate is 21.2 MHz, and the SNR is about 63 dB. Figure 4(d) illustrates

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autocorrelation trace that the direct output after OC2 is the shortest in 1.0 μm by using materials SAs as mode locker, to our best knowledge. The pulse duration is measured to be 379 fs and TBP is 2.16.

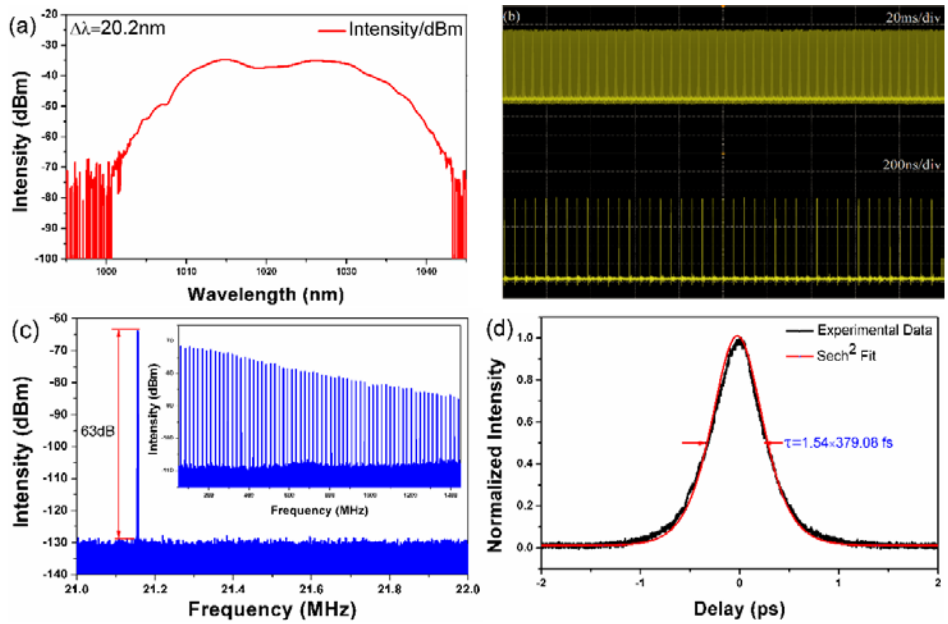

Fig. 4. Mode-locked pulse emission from the OC2 with a pump power of 70 mW. (a) The spectrum; (b) the typical pulse trains; (c) the corresponding RF spectrum at 21.16 MHz with an RBW of 1 Hz. Inset: RF spectrum at 21.16 MHz with RBW of 100 Hz; (d) the corresponding AC trace.

Considering that the pulses train after OC1 includes high chirp (TBP is 38.62) as well as getting shorter pulses, the DMS needs to be dechirped. After installing the external grating based compressor part, the pulse duration of laser can be compressed to extremely short. The duration of chirped pulse is about 4.14 ps. Figure 5 gives the autocorrelation trace of corresponding to dechirped pulses. The duration of the dechirped pulse is 175 fs, which is fitted by a sech^2 temporal profile. Owing to the compressor efficiency of 64% and the lower output power of OC2, the dechirped pulse of OC2 with existing intensity of autocorrelation could not be measured.

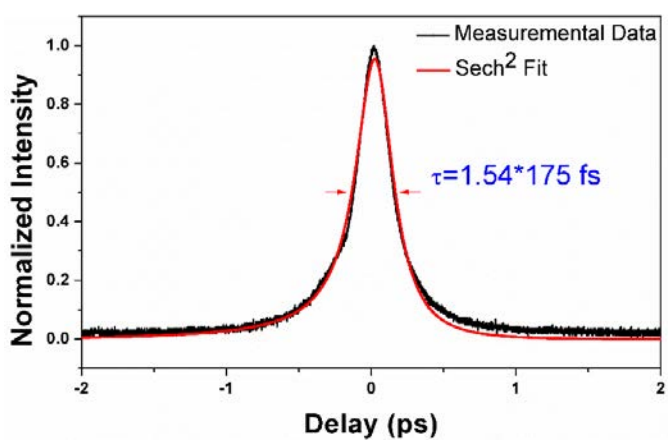

Fig. 5. The corresponding autocorrelation trace of the pulse after outside cavity compressing.

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4. Conclusion

In conclusion, we have experimentally demonstrated sub-200 femtosecond pulse generated from passively mode-locked YDF laser with SWCNTs as the mode locker in DMS regime for the first time, to the best of our knowledge. Stable DMSs with pulse duration of 4.14 ps and 379 fs were generated directly from OC1 and OC2 at 70 mW pump power, respectively. The dechirped pulse duration (OC1) is 175 fs via a grating pair compressor at the central wavelength of 1030 nm. It is the shortest pulse duration obtained from YDF laser based on broadband SAs by far.

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