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Nanotube mode locked, wavelength-tunable, conventional and dissipative solitons fiber laser

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A B S T R A C T

We report the generation of widely wavelength tunable conventional solitons (CSs) and dissipative solitons (DSs) in an erbium-doped fiber laser passively mode-locked by nanotube saturable absorber. The tuning ranges of CSs and DSs are ~15 and ~25 nm, respectively. In anomalous dispersion regime, the output CS exhibits symmetrical spectral sidebands with transform-limited pulse duration of ~1.1 ps. In the contrastive case of normal dispersion regime, the DS has rectangular spectrum profile and large frequency chirp, which presents pulse duration of ~13.5 ps, and can be compressed to ~0.4 ps external to the cavity. This fiber laser can provide two distinct types of tunable soliton sources, which is attractive for practical applications in telecommunications.

1. Introduction

Ultrafast-pulse lasers with spectral tuning capability have widespread applications in biomedical diagnostics, metrology, and telecommunications [1–3]. Passively mode-locked fiber lasers are convenient and powerful sources of ultrafast pulses. Various saturable absorbers (SAs), including semiconductor saturable absorber mirrors (SESAMs), single-walled carbon nanotubes (SWNTs), graphene, MoS_2, topological insulator, and black phosphours have been utilized to realize the passive mode locking [4–10]. Currently, the dominant technology is based on SESAMs [11,12]. However, SESAMs generally have a limited bandwidth, and require complex packaging. A simple, broadband alternative is to use SWNTs. In SWNTs the diameter controls the bandgap, thus, defining the operating wavelength [13,14]. Wideband tunability is possible using SWNTs with a wide diameter distribution [15,16].

Soliton operation of mode locked fiber lasers has been theoretically predicted and experimentally investigated previously [17–21]. Conventional solitons (CSs) are formed as a result of the balance between the anomalous dispersion and fiber nonlinearity [22]. Generally, the CS displays clear spectral sidebands, exhibits a $sech^2$ temporal profile, and is chirp-free [23]. Han *et al.* have proposed a sideband-controllable fiber laser by using chirped fiber Bragg gratings (CFBGs), in which each side of the spectral sidebands can be removed by virtue of using a CFBG with proper dispersion [24]. Recently, dissipative solitons (DSs) have been observed in large normal dispersion fiber lasers and the formation of DSs is the mutual interactions among normal dispersion, fiber nonlinear effect, laser gain, and losses [25,26]. DSs exist in dissipative systems, hence, their dynamics is remarkably different from that of CSs. DSs are generally characterized as having steep spectral edges, large pulse duration, and strong frequency chirp [27,28]. Renninger *et al.* have theoretically analyzed the pulse-shaping mechanism of the DSs governed by the cubic-quintic Ginzburg-Landau equation [29]. The robust dissipative soliton molecules exhibiting as the steep spectral edges have been investigated numerically and observed experimentally by Liu [30]. Furthermore, wavelength tunable solitons in mode-locked fiber lasers have been reported by exploiting tunable bandpass filter, unbalanced Mach–Zehnder interferometer, or a Sagnac fiber filter [31–33]. Wang et al. have presented a ~2.4 ps nanotube-mode-locked fiber laser that is tunable from 1518 to 1558 nm [34]. Sun et al. have demonstrated a ~1 ps CS fiber laser mode-locked by graphene based SA, which is wavelength tunable between 1525 and 1559 nm [35]. Continuous wavelength tunable DSs from 1570 to 1600 nm was achieved in an erbium doped fiber (EDF) laser mode locked with few layer graphene [36]. However, to the best of our knowledge, there is no report that both the wavelength tunable CSs and DSs are delivered from a nanotube-mode-locked fiber laser.

In this paper, we present an ultrafast fiber laser mode-locked by nanotube SA, delivering wavelength tunable CSs and DSs over ranges of ~15 and ~25 nm, respectively. Soliton propagation in the laser cavity has two optional routes with different length and dispersion. The CS exhibits clear Kelly sidebands with spectral bandwidth of ~2.4 nm and pulse duration of ~1.1 ps, while the DS shows steep spectral edges with

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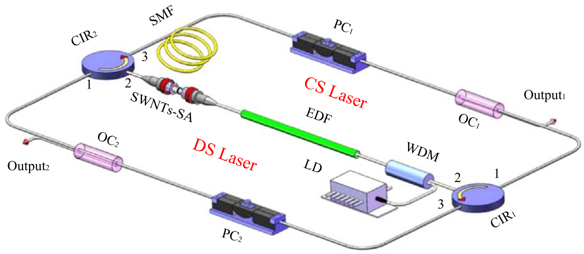

Fig. 1. Schematic diagram of the two-color mode-locked fiber laser. EDF, erbium-doped fiber; SMF, single-mode fiber; WDM, wavelength-division multiplexer; SWNTs-SA, single-walled carbon nanotubes-based saturable absorber; CIR, circulator; LD, laser diode; OC, output coupler; PC, polarization controller.

spectral bandwidth of ~10 nm. The pulse duration is ~13.5 ps, and can be further compressed to 0.4 ps. Compared with constructing independent tunable CS and DS fiber laser, the proposed scheme is very simple and attractive for telecommunications.

2. Experimental setup

The schematic diagram of the two-color mode-locked fiber laser is shown in Fig. 1. The laser consists of two ring resonators with one common branch, which includes a segment of 17-m EDF, pumped by a 980-nm laser diode (LD) using a wavelength division multiplexer (WDM), and a packaged SWNTs-SA as a mode locker. The damage threshold peak power of the SA is ~570 MW/cm^2. The CS loop is based on a piece of 51-m single-mode fiber (SMF), a polarization controller (PC_1), and a 10% port of output coupler (OC_1). The DS loop is based on a piece of 14-m SMF, a PC_2, and a 10% port of output coupler (OC_2). Two optical circulators (CIRs) are used to realize dual-loop configuration and to maintain unidirectional laser operation. The dispersion parameters D for EDF and SMF are about −16 and 17 ps/(nm·km), respectively.

3. Experimental results and discussion

The loss between the CS laser and the DS laser is caused by the PCs-induced twists and pressures in the fiber. When the PC_2-induced loss is strong while PC_1-induced loss is negligible, light propagates in the cavity from port $CIR_1 \rightarrow 1 \rightarrow 2 \rightarrow CIR_2 \rightarrow 2 \rightarrow 3 \rightarrow OC_1$. In this case, the length and net dispersion of the cavity are 68 m and −0.8 ps^2, respectively, and the CS tends to be formed in the proposed laser. Contrastively, when the PC_1-induced loss is strong while PC_2-induced loss is negligible, light propagates in the cavity from port $CIR_2 \rightarrow 1 \rightarrow 2 \rightarrow CIR_1 \rightarrow 2 \rightarrow 3 \rightarrow OC_2$. In this case, the length and net dispersion of the cavity are 31 m and 0.05ps^2, respectively, and the DS can be easily formed in the proposed laser. The evolutions of the two solitons are not synchronous in the cavity, and the formations of the two solitons are independent. In the experiment, two types of solitons cannot be simultaneously delivered from the laser by appropriately adjusting the pressure imposed by PCs and increasing the pump power.

Self-started mode-locking operation is observed from the OC_1 at the pump power of P=18 mW. By appropriately tuning the orientations of the PCs, the proposed laser delivers the pulses with the different central wavelengths. The typical output spectra are shown in Fig. 2, with the central wavelengths λ_{1-5} of 1561, 1564, 1568, 1571, and 1576 nm, respectively. We note that the continuous tuning range is about 15 nm. The optical spectra of the pulses are described by the appearance of clear Kelly sidebands, which is the typical feature of CSs formed in anomalous dispersion regime [37,38].

Fig. 3 shows a typical case of CS at the central wavelength λ=1573 nm. Fig. 3(a) is an output spectrum, with a 3-dB spectral bandwidth of ~2.4 nm. Fig. 3(b) is the corresponding AC trace of the sech^2-shaped fit curve. The pulse duration is given as ~1.1 ps. The calculated time-bandwidth product (TBP) is ~0.32, which is value of

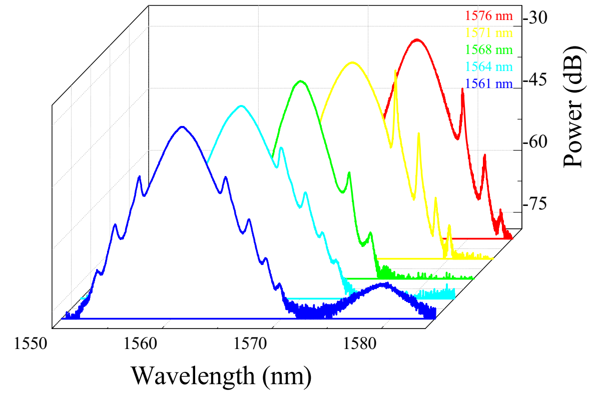

Fig. 2. Output spectra of CSs at five different wavelengths. The central wavelengths of λ_{1-5} are 1561, 1564, 1568, 1571, and 1576 nm, respectively.

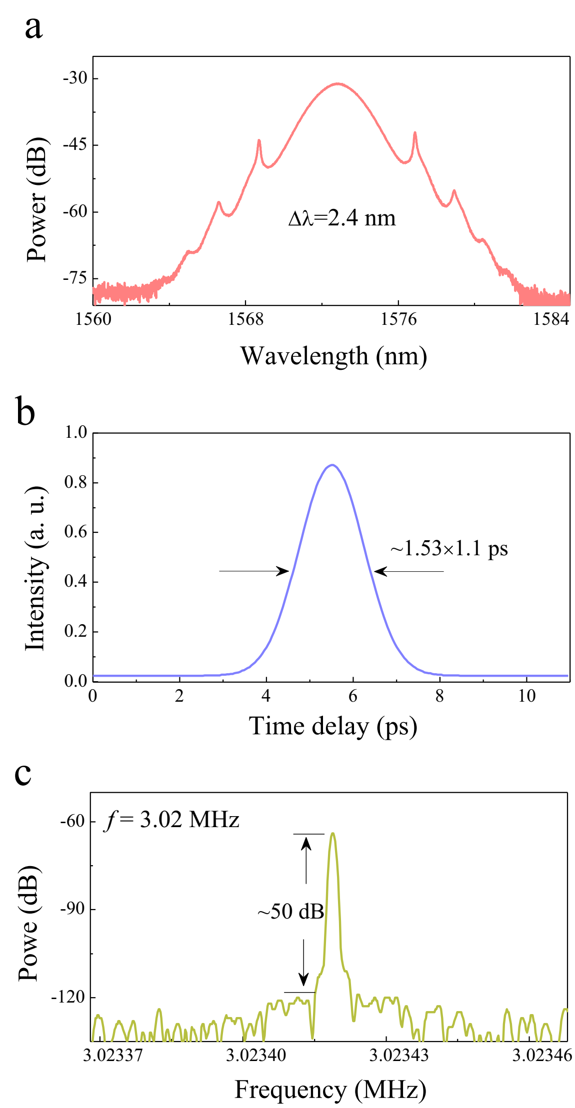

Fig. 3. (a–c) The optical spectrum, AC trace, and RF spectrum, respectively, of the CS at the central wavelength λ=1573 nm.

the transform-limited chirp-free pulse. As described in Fig. 3(c), RF peak with a signal-to-noise ratio of ~50 dB is observed. The fundamental repetition rate is 3.02 MHz, corresponding to 330 ns round-trip time. Based on aforementioned results, we infer that the fiber laser operates at a stable CS mode-locking state. The average output power