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Carbon-nanotube-based passively mode-locked fiber lasers modulated with sub-loop

Yudong Cui

State Key Laboratory of Transient Optics and Photonics, Xi'an Institute of Optics and Precision Mechanics, Chinese Academy of Sciences, Xi'an 710119, China

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ABSTRACT

We have proposed a carbon-nanotube-based passively mode-locked fiber laser, which consists of two fiber ring resonators, for the first time to author's best knowledge. The proposed laser in the main cavity is coupled with a fiber sub-loop, which is connected with a 2 × 2 optical coupler. Without the sub-loop, uniform-spaced conventional solitons are achieved in the fiber ring laser. With the sub-loop, the fiber laser generates a train of pulses modulated with a periodic envelop. The modulation period and pulse-pulse separation are ∼160 and ∼4.3 ns, which are determined by the lengths of the main cavity and the sub-loop, respectively.

1. Introduction

Fiber lasers have many unique merits, such as compact configuration, heat dissipation and high reliability [1–5], which have been exploited applications in optical communications [3], ultra-narrow waves [4], optical sensors [5] and nonlinear optics [6,7]. Especially, the passively mode-locked lasers have been widely investigated for decades, owing to the ability of delivering ultrafast pulses [8–10]. Nonlinear optical loop mirror [11], nonlinear polarization rotation technique [12,13], semiconductor saturable absorber mirrors (SESAMs) [14], single-walled carbon nanotubes (SWNTs) [15,16] and graphene [17,18] are generally employed as effective saturable absorbers to generate ultrashort pulses. Recently, SWNTs and graphene were discovered and have been used as the excellent alternatives of SESAMs which suffer from the cost-ineffective and the narrow bandwidth [16,19]. With a compactness and low-cost transmission-type SWNTs-based mode locker, Zeng *et al.* realized a bidirectional fiber ring laser [15].

The generation of various types of pulses, such as conventional soliton (CS) [20–23], stretch pulses [24], self-similar pulse [25] and dissipative soliton (DS) [26–28], depend on the settings of net cavity dispersion. The evolution of pulses in fiber lasers with net-anomalous, near-zero and net-normal cavity dispersion have been numerically and experimentally investigated in the last few years [2,12,24,29–31]. Additionally, some novel types of pulses, such as wave-breaking-free pulses [32] and ultra-broadband high-energy pulses [33] have been proposed recently. To face the practical application, various designs of fiber laser were proposed, achieving multi-type [34], multi-wavelength [16,35] and high repetition rate (HRR) [36,37] pulses. A SESAM mode-locked fiber laser fabricated with three-port circulator, which can simultaneously emit CS and DS, was proposed by Mao *et al.* [34]. Liu *et al.* have reported a SWNT-based all-fiber oscillator, offering versatile pulse sources with different wavelengths that can be tuned by stretching fiber Bragg gratings [16]. Peccianti *et al.* [37] have recently realized HRR pulses in a fiber laser coupled with a high-*Q* factor microcavity resonator. Optical ring resonators were generally utilized in fiber laser to achieve optical time delay, photonic biosensors and filters with tailored response [38,39].

In this paper, we propose an all-fiber laser mode locked with SWNTs, which includes a main fiber ring cavity and a fiber sub-loop. The sub-loop is fabricated by splicing two 10% ports of a 2 × 2 optical coupler (OC). Without the sub-loop, typical CSs are achieved in the main ring cavity. With the sub-loop, the fiber laser generates a train of pulses modulated with a periodic envelop. The modulation period and the adjacent pulses separation are ∼160 and ∼4.3 ns, respectively. The corresponding radio frequency (RF) spectrum shows that the fundamental repetition rate is ∼6.2 MHz and the period of modulation is ∼230 MHz. They depend on the modulation of the sub-loop to the laser in the main ring cavity. The experimental observations confirm that the modulation period and the adjacent pulses separation vary with the lengths of two rings.

E-mail address: cuiyudong6@gmail.com

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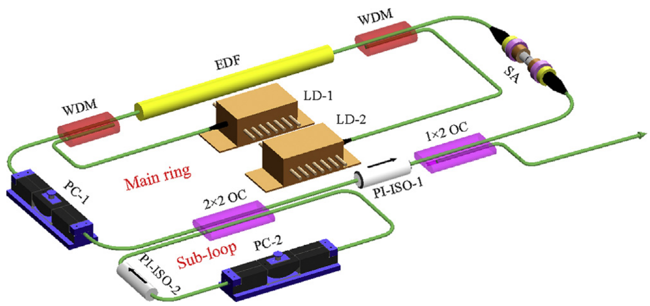

Fig. 1. Experimental setup which consists of a main ring cavity and a sub-loop. LD: laser diode; WDM: wavelength-division multiplexer; EDF: erbium-doped fiber; PC: polarization controller; OC: optical coupler; PI-ISO: polarization-independent isolators; SA: saturable absorber.

2. Experimental setup

Fig. 1 shows the schematic diagram of the proposed laser where a fiber sub-loop is coupled to a main fiber ring cavity through a 2×2 fiber optical coupler (OC). The main fiber ring consists of a 20-m-long erbium-doped fiber (EDF) with a 6 dB/m absorption at 980 nm as the gain medium, a polarization controller (PC) to optimize the linear birefringence, a polarization-independent isolator (PI-ISO) to ensure unidirectional operation of the ring, a saturable absorber (SA) to generate mode-locked pulses and a fused 90/10 OC as the output port. The saturable absorber (SA) based on the SWNTs is fabricated as the method in Refs. [15,16]. Via two 980/1550 nm wavelength-division multiplexer (WDM), the laser is pumped by two 980 nm laser diodes (LDs). All other fibers are the standard single-mode fibers (SMFs). The dispersion parameters D for EDF and SMF are about −9 and 17 ps/(nm km) at 1550 nm, respectively. The length of main ring is ~33 m, and the net dispersion is about $-0.06\ ps^2$.

The fiber sub-loop is fabricated by splicing two 10% ports of a 2×2, 90/10 OC, and the 90% ports are connected in the main cavity. There are only a PC and a PI-ISO in the sub-loop. All the fiber is SMF, and the length of the sub-loop is ~0.88 m. An optical spectrum analyzer, a commercial autocorrelator (AC), a radio-frequency (RF) analyzer, and a 6-GHz digital oscilloscope with a photodiode detector are used to monitor the laser outputs.

3. Experimental results and analysis

When the fiber sub-loop is removed, this is a typical passively mode-locked fiber ring laser. Mode locking of the laser can be self-started as the pump power is increased to 20 mW. At this moment, multiple pulses are generally formed in the cavity. However, through carefully decreasing the pump power and adjusting the PC state, the number of soliton pulses can be reduced and eventually a single pulse operation can be obtained. Fig. 2a shows a typical output spectrum of CS. The spectrum is centered at 1562 nm with a 3-dB bandwidth 3.9 nm. Obvious sidebands can be seen on the spectrum, which reflects the soliton feature of pulses. It is originated from the constructive interference of the soliton and dispersive waves [22,40]. The corresponding AC trace of the CS is demonstrated in Fig. 4b. By using a $sech^2$ fit, the duration of the pulse is given as 1.3 ps. The time bandwidth product of the CS is calculated as 0.62, indicating that the output CS is slightly chirped. The output pulse train is depicted in Fig. 2c. The pulse train has a uniform interpulse interval of ~160 ns which is consistent with the cavity round-trip time. Fig. 2d is the fundamental RF spectrum with the 1 Hz resolution for the CS. The fundamental repetition rate of CS is ~6.2 MHz with a peak-to-background ratio of ~60 dB. The inset in Fig. 2d is the wideband RF spectrum up to 500 MHz. No spectral

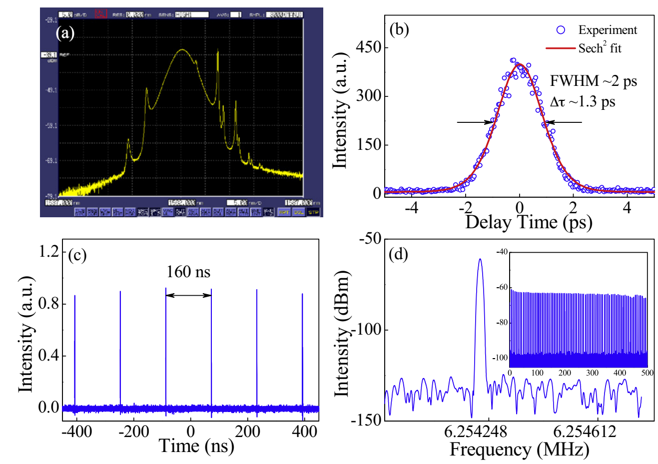

Fig. 2. Experimental results without the fiber sub-loop: (a) optical spectrum, (b) oscilloscope trace, (c) fundamental RF spectrum. Inset: wideband RF spectrum up to 500 MHz and (d) autocorrelation trace of the laser output.

modulation is observed, indicating the laser operates well in the CS mode-locking regime.

When the laser operates with a sub-loop, the operation state is completely different, as demonstrated in Fig. 3. Once the two 10% ports of the 2×2 OC are connected, the appearance of optical spectrum emerges as that in Fig. 3a. Compared with the spectrum in Fig. 2a, the sideband disappears, central wavelength changes slightly, and the bandwidth of spectrum reduces to ~1.3 nm. With appropriate tuning the PC in sub-loop, a sequence of pulses modulated with a periodic envelope can be observed on screen of oscilloscope, as displayed in Fig. 3b. Fig. 3b and c shows that the period of modulation and the separation of adjacent pulses are ~160 and ~4.3 ns, respectively. It is found that the separation of adjacent pulses corresponds to the length of sub-loop and the period of modulation is just in agreement with the lengths of main ring laser. The RF spectrum also evolves with a periodic envelop, as shown in Fig. 3d. The fundamental repetition rate is ~6.2 MHz, which is almost equal to the results without sub-loop. The period of modulation is ~230 MHz, corresponding to the repetition rate of the short sub-loop. That can be easily distinguished from Q-switched mode-locking [41] and bound state [42], although they have a resembling shape of pulse train or RF spectrum. The results

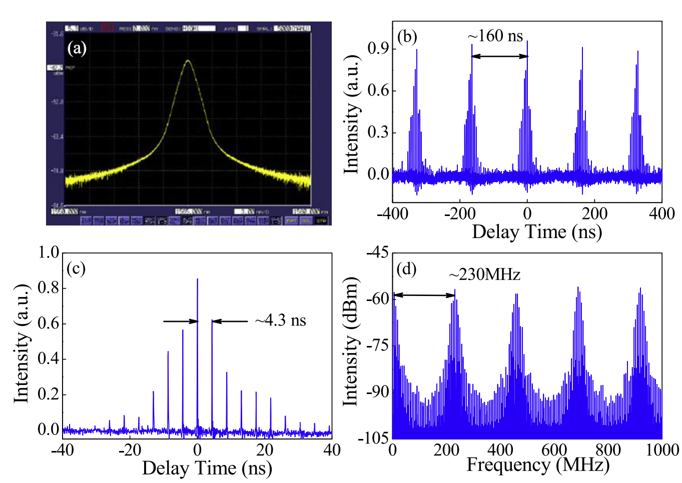

Fig. 3. Experimental results with the fiber sub-loop: (a) optical spectrum, (b) oscilloscope trace of pulse train, (c) zoom in one packet of pulses and (d) RF spectrum at a span of 1 GHz.