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Investigations of switchable fiber soliton laser mode-locked by carbon nanotubes

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ABSTRACT

We have numerically and experimentally investigated a switchable erbium-doped fiber (EDF) laser mode-locked by single-walled carbon nanotubes for the first time to our best knowledge. Depending on the pump power, the central wavelength of the mode-locked pulse can be switched from about 1531 to 1557 nm. The formation and evolution of the switchable soliton operation are investigated numerically by solving the extended nonlinear Schrödinger equation with the appropriate gain profile. Numerical results demonstrate that the switchable mode-locking operation is attributed to the variation of the gain spectrum of EDF, agreeing well with the experimental observations.

1. Introduction

Fiber-based lasers attract extensive attention because they can deliver the ultrashort pulses [1–3], the multiple wavelengths [4–6], and the ultra-narrow laser source [7]. The nonlinear phenomena and nonlinear pulse evolutions in fiber are the rich and fascinating subjects [8–11]. Especially, with the capability of generating self-starting ultra-short pulses, passively mode-locked fiber lasers have attracted a great deal of research interests [12–14]. Various techniques, such as nonlinear polarization rotation (NPR) technique [15,16], nonlinear optical loop mirror (NOLM) [17], semiconductor saturable absorber mirrors [18], single-walled carbon nanotubes (SWNTs) [19,20], and graphene [21], graphite [22] and other nano-scale carbon materials [23], have been exploited for stable passive mode locking. Among the various methods, SWNTs and graphene have been widely investigated due to the advantages of broad operating range, easy fabrication, mechanical and environmental robustness, and low saturation power [24,25]. The recent investigations show that the graphene-nanotube composite has the capacity of preventing aggregation of graphene due to van der Waals forces. So Cui et al. have proposed a fiber soliton laser mode-locked by the mixture of graphene and SWNTs [26].

With appropriate management of net cavity dispersion, various pulses including conventional soliton (CS) [25,27], stretched pulse [28], self-similar pulse [29], and dissipative soliton (DS) [30,31] have been demonstrated successively. In addition, some novel types of pulses, such as the DS resonance [13,32] wave-breaking-free pulses [2,8] ultra-broadband high-energy pulses [3,33] have been proposed recently. Hyperbolic-secant CS with spectral sidebands is formed due to the balance between positive nonlinearity and negative fiber dispersion [27]. However, each side of the spectral sidebands could be eliminated by using a chirped fiber Bragg grating (CFBG) [34]. While as to the formation of DS, the balance of gain and loss coexisting in the dissipative system plays an essential role [30]. Wang et al. have experimentally observed four different types of pulses in the same DS fiber laser [35]. Moreover, by utilizing CFBG and four-port circulator, the coexistence of CS and DS has also been achieved by Mao et al. [36].

On the other hand, various pulse operations such as single pulse [2], multiple pulses [37], bound-state pulses [38], pulse molecule [39], bunch-state pulses [40], and harmonic mode-locking [41] have been observed by changing pump power. Liu has numerically and experimentally investigated the CS formation in ultralong anomalous-dispersion fiber lasers [42] and the DS formation in the large net-normal-dispersion fiber lasers [43]. Additionally, wavelength tunable fiber lasers mode locked with the NPR technique [44] and NOLM [45] have been realized by adjusting the cavity birefringence. By pressing on CFBG, wavelength-tunable fiber laser mode-locked with graphene was also realized by He et al. [46].

In this paper, we have numerically and experimentally investigated a switchable soliton laser based on a SWNTs mode-locker for the first time to our best knowledge. The proposed fiber soliton laser operates at the central wavelength of ~1557 nm when the pump power is low. But it switches to the central wavelength of ~1531 nm when the pump power increases to ~32 mW. The switchable operation can be attributed to the variation of the gain of erbium-doped fiber (EDF) related to pump power. By solving the extended nonlinear Schrödinger equation and taking the gain profile

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into account, the formation and evolution of the switchable operation are demonstrated by the simulations. The numerical results well confirm the experimental observations.

2. Experimental setup

The proposed fiber laser system is shown schematically in Fig. 1. A 980 nm laser diode (LD) is coupled into the laser with 980/1550 nm wavelength-division-multiplexer (WDM). A ~5-m-long EDF with the dispersion D of ~−9 ps/nm/km contributes to the gain media. The SWNTs mode locker is formed by sandwiching a ~2 mm^2 free-standing SWNT-polymer film between two FC/PC fiber ferrules inside a connector. A polarization controller (PC) is placed in front of the SWNTs mode locker to optimize the mode-locking conditions. The 10% port of a coupler is used to output the signal. A polarization-independent isolator (PI-ISO) is inserted into the cavity to ensure unidirectional operation of the ring. All other fibers are standard single-mode fiber with the total length of ~55 m and D of 17 ps/nm/km. So the total length of the cavity is about 60 m, and the net cavity dispersion is estimated as −1.14 ps^2. An optical spectrum analyzer, an autocorrelator, a 6-GHz oscilloscope, a radio-frequency (RF) analyzer, and a 10-GHz photodetector are employed to monitor the laser output simultaneously.

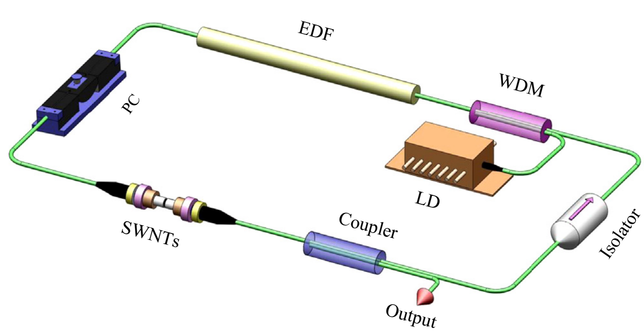

Fig. 1. Schematic diagram of the experimental setup.

3. Experimental results and analyses

With appropriate orientation and pressure settings of the PC states, the continuous wave emission at wavelength of ~1557 nm is obtained when the pump power is 9 mW. By further increasing the pump power to 12 mW, self-starting mode-locking operation can be easily achieved. As shown in Fig. 2(a), we can observe that several pairs of sidebands are distributed at both sides of the spectrum, which is the typical characteristic of CS. The central wavelength locates at 1557 nm and the 3-dB bandwidth is ~2.5 nm. The autocorrelation trace in Fig. 2(b) has a full width at half maximum (FWHM) of ~2.1 ps. If a sech^2 profile is assumed for fitting, the pulse duration is estimated as 1.36 ps. The pulse trains in Fig. 2(c) show that the laser operates at a multi-pulses mode-locking state. The slight nonuniformity of the measured pulse intensity is caused by the limit of the electronic detection. Fig. 2(d) illustrates that the fundamental repetition is 3.381093 MHz, which corresponds to the total cavity length of ~60 m. The signal/noise ratio is higher than 60 dB, indicating that a stable mode locking is achieved.

The operating wavelength switches from 1557 nm to 1531 nm when power is increased to 32 mW. The typical optical spectrum, autocorrelation trace, oscilloscope traces, and RF spectrum are shown in Fig. 3. The central wavelength, spectral width, and pulse duration are given as 1531 nm, 2.4 nm, and 1.31 ps, respectively. The oscilloscope traces in Fig. 3(c) denote that the fiber laser emits multiple pulses. In this state, the fundamental repetition rate is 3.381350 MHz, as shown in Fig. 3(d). It is worth noting that the pulses of two wavelengths operate at different repetition rates with

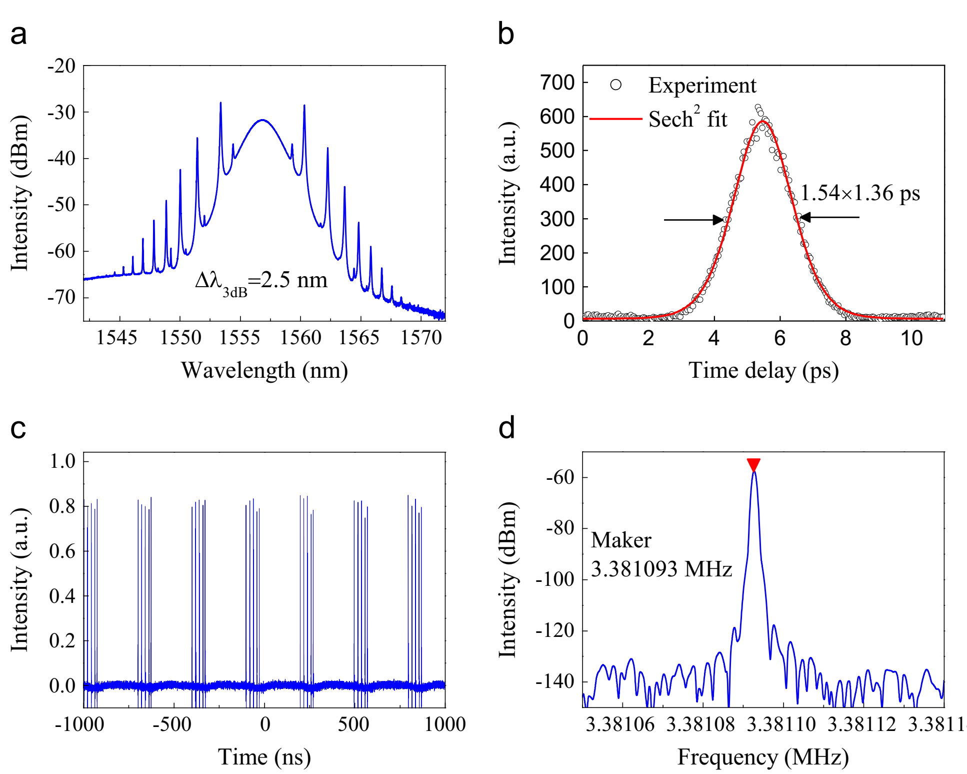

Fig. 2. Mode-locking operation at 1557 nm when the pump power is 12 mW. (a) Output optical spectrum, (b) autocorrelation trace, (c) oscilloscope traces, and (d) fundamental RF spectrum.