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Discussion

Observation of dual-wavelength solitons and bound states in a nanotube/microfiber mode-locking fiber laser

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A B S T R A C T

We report on the experimental observation of dual-wavelength soliton and the phase-locked bound state in an all-fiber laser mode-locked by a carbon nanotubes/microfiber saturable absorber. The operation wavelengths are strongly dependent on the intracavity loss. By adjusting an attenuator to increase the intracavity loss, mode-locking wavelength shifts from 1557 to 1531 nm. With the appropriate pump power and intracavity loss, dual-wavelength solitons are achieved simultaneously. In addition, the phase-locked bound-state solitons are also observed at the two wavelengths. The pulse separation and phase difference are related to the first-order Kelly sidebands.

1. Introduction

Ultrashort all-fiber lasers possess inherent merits of good reliability, high beam quality, as well as excellent heat dissipation, and offer a perfect platform for the generation of ultrashort pulses and nonlinearity investigations [1–5]. According to the nonlinear Schrödinger equation, the balance of fiber nonlinearity and anomalous dispersion can support the transmission of conventional solitons (CSs) [6–10]. Generally, CSs emitted from the fiber lasers under anomalous dispersion exhibit the Sech^2 temporal and spectral profiles with discretely distributed Kelly sidebands [7–9]. These sidebands originate from the constructive interference between the solitons and dispersive waves which are shed from the solitons due to the periodic disturbance [10–12]. To date, various soliton operations have been observed, such as vector solitons [13], bound-state solitons [14–17], and harmonic mode locking [18,19]. The stable bound states have been extensively investigated because of their potential applications in optical communications and high-resolution optics for coding and transmission of information in high-level modulation formats [20,21]. The soliton molecules with the fixed separations [22] and the slightly variation separations [16], as well as the phase differences of 0 [20], π [15], and π/2 [14], have been experimentally observed.

To passively initiate the ultrashort pulse operations in fiber lasers, various saturable absorbers (SAs) have been explored, such as nonlinear optical loop mirror [23–25], nonlinear polarization rotation technique [26–29], semiconductor saturable absorber mirrors [30,31], single-wall carbon nanotubes (SWNTs) [32–35], graphene [36–38], and the mixture of nanotube and graphene [9,39]. Amongst the aforementioned mode-locking technology, SWNTs and graphene have attracted lots of interest due to the unprecented advantages of broad operating range, low saturation power, electrically tunable modulation depth, and environmental robustness [32,40]. The mode lockers made of the transmission-type SWNT–polymer composite films are widely employed in fiber lasers for the easy fabrication processes [41,42]. However, the damage threshold is low for the film between the fiber ferrules, which limits the generations of high energy pluses [41,43]. Recently, a SWNT-SA was made by depositing SWNTs around a microfiber via the evanescent light [43]. With the assistance of microfiber, the damage threshold was substantially elevated [44] and the interaction length between the light and nanotube via the evanescent field could be effectively increased [44,45].

A wide variety of single wavelength fiber lasers has been investigated theoretically and experimentally [46]. However, dual- or multi-wavelength all-fiber lasers play important roles in numerous areas, including wavelength-division-multiplexed systems, fiber sensing, and spectrum detection [47–49]. With the spectral filtering of chirped fiber Bragg grating, multi-wavelength

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nanotube-mode-locked fiber laser was proposed by Liu et al. [49]. Recently, dual-wavelength ultrafast fiber lasers were reported, which mainly depend on the natural fiber birefringence in the laser cavity [23,50]. In these cases, the wavelengths could be changed by adjusting the intracavity birefringence [23]. Fedotov et al. proposed the spectrum-, pulsewidth-, and wavelength-switchable all-fiber mode-locked Yb laser with fiber based birefringent filter [51]. In addition, the operation wavelength can also be determined by the pump power which is related to the gain profile in an Erbium-doped fiber (EDF) laser [52].

In this paper, we propose a fiber laser mode-locked with a SWNT-SA fabricated by depositing SWNTs around a microfiber. It is found that the operation wavelength depends on the intracavity loss in the proposed laser. The mode locking is self-started at the wavelength of 1557 nm. By adjusting an intracavity attenuator to increase the loss, mode-locking wavelength is switched to 1531 nm. Successively, with the appropriate loss and pump power, dual-wavelength silitons are achieved. In addition, bound-state solitons are observed at either 1557 or 1531 nm when the pump power is ~28 mW. The pulse separation and phase difference are related to the first-order Kelly sidebands of the solitons.

2. Experimental setup

Fig. 1 shows the schematic diagram of the proposed carbon nanotube-mode-locked fiber laser. The gain medium is a 5-m EDF with the 6 dB/m absorption at 980 nm. The laser is pumped by a 980 nm laser diode (LD) through a 980/1550 nm wavelength-division-multiplexed (WDM) couplers. 10% port of a fused 90/10 optical coupler (OC) is set as the output port. A polarization controller (PC) is employed to optimize the linear birefringence. A polarization-independent isolator (PI-ISO) ensures the unidirectional operation of the laser. The homemade SWNT/microfiber SA acts as a mode locker of the proposed laser. All other fibers are the standard single-mode fibers (SMFs). The dispersion parameters *D*

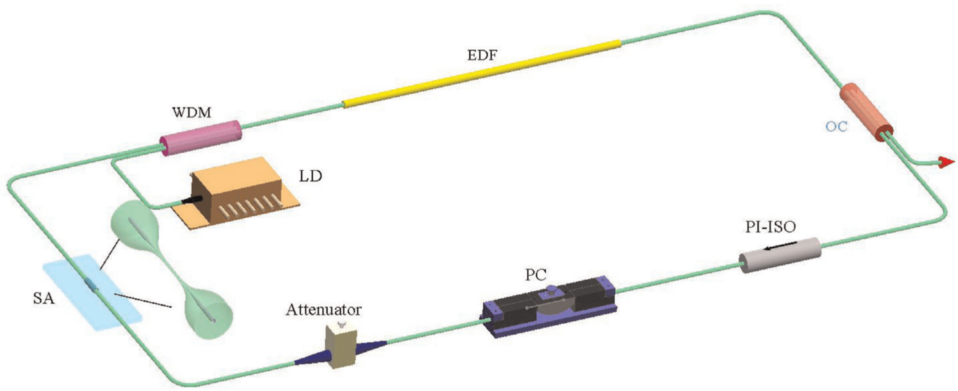

Fig. 1. Experimental setup of the proposed all-fiber laser. LD, laser diode; WDM, wavelength-division multiplexer; EDF, erbium-doped fiber; OC, optical coupler; PI-ISO, polarization-independent isolators; PC, polarization controller; SA, saturable absorber.

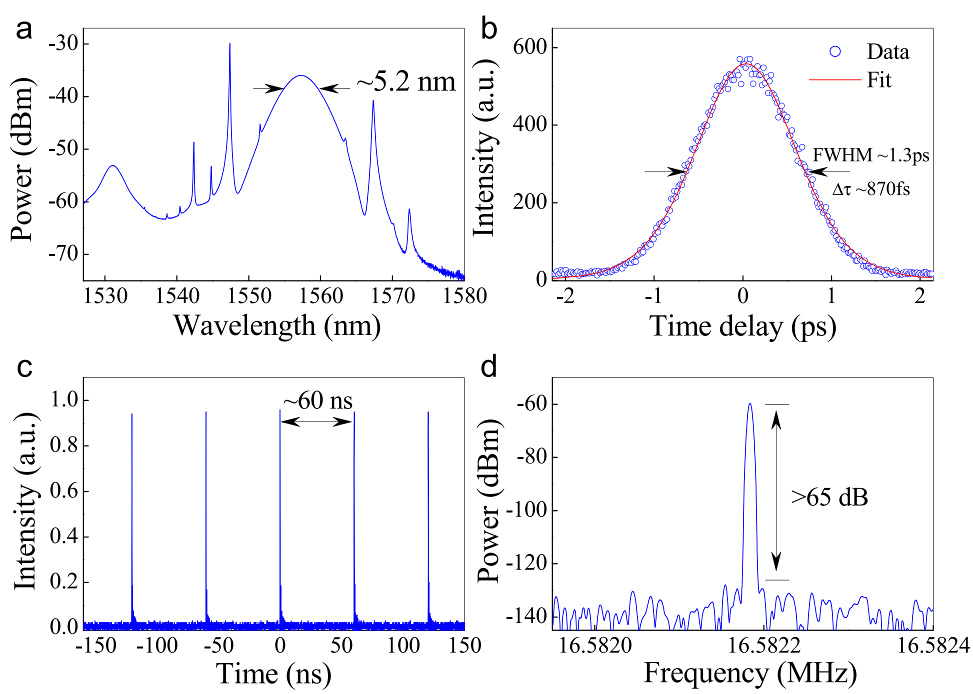

Fig. 2. Experimental results of CSs at 1557 nm. (a) Optical spectrum, (b) autocorrelation trace, (c) oscilloscope trace, and (d) fundamental RF spectrum of the laser outputs.