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All-fiber laser simultaneously delivering multi-wavelength solitons

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ABSTRACT

All-fiber triple-wavelength laser mode-locked by a nonlinear amplifier loop mirror is proposed and demonstrated experimentally for the first time to author's best knowledge. By means of chirped fiber Bragg gratings in the intra-cavity and extra-cavity, three kinds of solitons with different wavelengths are simultaneously delivered from the proposed laser. The central wavelengths of solitons are 1539.5, 1549.5, and 1559.5 nm with the pulse durations of 6.2, 4.2, and 5 ps and the spectral bandwidths of 0.4, 0.7, and 0.5 nm, respectively. The experimental observations show that the all-fiber triple-wavelength laser is very stable in the long-term operation and is convenient for practical applications.

1. Introduction

Fiber lasers have been broadly investigated for many applications, such as optical communications [1], optical sensors [2], and nonlinear optics [3,4], because of their compactness [5], simplicity [6], and ability to generate ultrafast pulses [7,8]. They can generate either pulses (e.g., hyperbolic-secant solitons [9], stretched pulses [10], and parabolic pulses [11]) or continuous waves (e.g., ultranarrow wavelength [12], dual-wavelength [13], and multi-wavelength [14]). Mode locking technique is a superior way to generate repetitive ultrashort pulse trains, in which the saturable absorbers (SAs) have been widely used as mode lockers [15–27]. Nonlinear optical loop mirror (NOLM) [15], nonlinear polarization rotation (NPR) technique [16,17], semiconductor saturable absorber mirrors (SESAM) [23], single-walled carbon nanotubes (SWNTs) [24,25], graphene [26], and graphene-nanotube mixtures [27] can all act as effective SAs, which is used to realize the passive mode locking in fiber lasers. Based on a NOLM laser cavity, Seong et al. have observed the temporal bound solitons [15]. By virtue of the NPR effect, transient lasing regime between single-pulse and noise-like [16], nanosecond pulses [17], high-energy pulse [18], dissipative soliton (DS) molecules [19], and wave breaking pulse [20] have been investigated in mode-locked fiber lasers. In a SESAM mode-locked fiber laser, Mao et al. have reported the simultaneous generation of conventional solitons (CS) [23]. By using the SWNTs, Zeng et al. have proposed a fiber laser delivering bidirectional solitons with distinct output characteristics [24]. Additionally, with a mixture of graphene-nanotube, DSs and CSs emitting from a bidirectional fiber laser have been obtained by Cui et al. [27].

Apart from the various kinds of laser cavity designs, different types of mode-locked pulses can be generated, and the pulse evolution both in temporal and frequency domains have been investigated extensively [28–32]. Usually, the formation and evolution of single-wavelength pulses have been reported in previous reports [33–35]. Liu have numerically and experimentally investigated the formation of CS in an ultralong anomalous dispersion fiber laser [28] and DS in normal dispersion fiber laser [29]. Cundiff et al. have experimentally observed the phase-locked temporal vector solitons in fiber lasers [30]. In addition, a peculiar operation state of mode-locked fiber lasers—soliton rains, has also been investigated by Chouli et al. [31]. Recently, multi-wavelength mode-locked fiber lasers have been widely applied in optical pump-probe measurement, coherent pulse synthesis, optical spectroscopy, dense wavelength-division-multiplexed fiber communication systems, fiber-optic sensors, and microwave photonics systems [36–38]. Especially, multi-wavelength erbium-doped fiber (EDF) lasers have been investigated widely due to their advantages such as low threshold and high power conversion efficiency [37]. Based on fiber Bragg gratings and high nonlinear photonic crystal fiber, a novel dual-wavelength EDF laser has been demonstrated by Liu et al. [37]. The picosecond and femtosecond solitons with different wavelengths have been achieved simultaneously by Chen et al. [38]. However, to our knowledge, no triple-wavelength mode-locked figure-eight fiber laser has been demonstrated.

In this letter, we propose an all-fiber laser system based on nonlinear amplifier loop mirror (NALM) incorporating chirped fiber Bragg gratings (CFBGs) to implement simultaneous three-wavelength solitons mode locking. The light propagation in the cavity has three optional routes. By appropriately changing the

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pressure imposed by polarization controllers (PCs), the three-wavelength CSs centered at 1539.5, 1549.5, and 1559.5 nm can be observed in the laser. The three-wavelength CSs exhibit Kelly soliton sidebands with the spectral bandwidths of 0.4, 0.7, and 0.5 nm, and the pulse durations of 6.2, 4.2, and 5 ps, respectively. The triple-wavelength laser system can provide three different pulse sources, which is convenient for practical applications.

2. Experimental setup

Fig. 1 shows the schematic diagram of the triple-laser system setup. It is an all-fiber figure-eight laser based on a passive unidirectional ring (UR) cavity that is coupled to a NALM through a 3-dB fiber coupler. The NALM consists of a 6-m-long EDF with a 6 dB/m absorption at 980 nm served as the gain medium, a wavelength-division-multiplexer (WDM), and a PC. The UR contains a fused optical coupler (OC) with 10% output ratio, a circulator, three PCs, and three CFBGs. The laser is pumped by a 980 nm laser diode (LD). All other fibers are the standard single-mode fibers (SMFs). The overall length of the NALM ring is ~14 m. The dispersion parameters D for EDF and SMF are about −9 ps/nm/km and 17 ps/nm/km at 1550 nm, respectively. Three CFBGs with a dispersion of 1.7 ps/nm are written on a 10-mm-length SMF. The bandwidths of three CFBGs are 1 nm, and the corresponding central transmittance wavelengths λ_{1-3} are 1539.5, 1549.5, and 1559.5 nm, respectively. The output wavelengths of the laser system are separated by means of another three CFBGs for characterization of individual wavelengths. An optical spectrum analyzer, a commercial autocorrelator (AC), a radio frequency (RF) analyzer, and a digital storage oscilloscope are employed to monitor the laser output.

3. Experimental results and analysis

The loss among the three CFBGs can be flexibly controlled by PC_1- and PC_2. When PC_1- and PC_2-induced loss is strong, light propagates in the circulator from port $1\rightarrow2\rightarrow CFBG_1\rightarrow2\rightarrow3$. The length and net dispersion of the cavity are about 32.1 m and -2.61 ps^2, respectively. By the other two PCs adjustment, CS tends to be formed at the reflection wavelength of $CFBG_1$. When PC_1-induced loss is negligible while PC_2-induced loss is strong, light propagates in the circulator from port $1\rightarrow2\rightarrow CFBG_1\rightarrow CFBG_2\rightarrow2\rightarrow3$. The length and net dispersion of the cavity are about 34.9 m and -2.67 ps^2, respectively. Through the other two PCs rotation, CS can be obtained at the reflection wavelength of $CFBG_2$. When PC_1- and PC_2-induced losses are negligible, light propagates in the circulator from port $1\rightarrow2\rightarrow CFBG_1\rightarrow CFBG_2\rightarrow CFBG_3\rightarrow2\rightarrow3$. The length and net dispersion of the cavity are about 39.1 m and -2.76 ps^2, respectively. As we further tune the other two PCs, CS can be achieved at the reflection wavelength of $CFBG_3$.

By appropriately adjusting the pressure imposed by PCs, three types of pulses all experience enough net gain in the cavity. Self-started three-wavelength CSs mode locking can be achieved simultaneously when the pump power exceeds the threshold. Fig. 2 shows, for example, the optical spectrum of the three-wavelength solitons observed at $P=200$ mW. The spectrum of the solitons is centered at 1539.5, 1549.5, and 1559.5 nm, which correspond to the reflection spectra of the $CFBG_1$, $CFBG_2$, and $CFBG_3$, respectively. The spectrum of

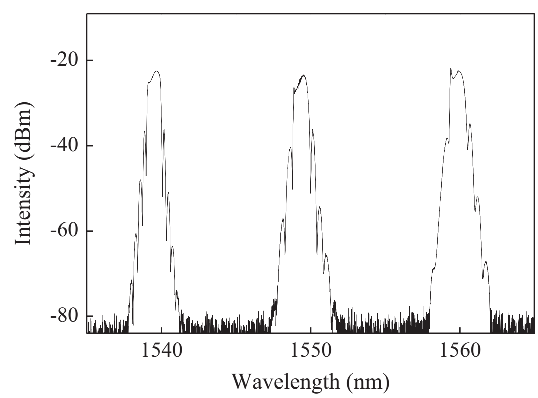

Fig. 2. Optical spectrum of the three-wavelength CSs.

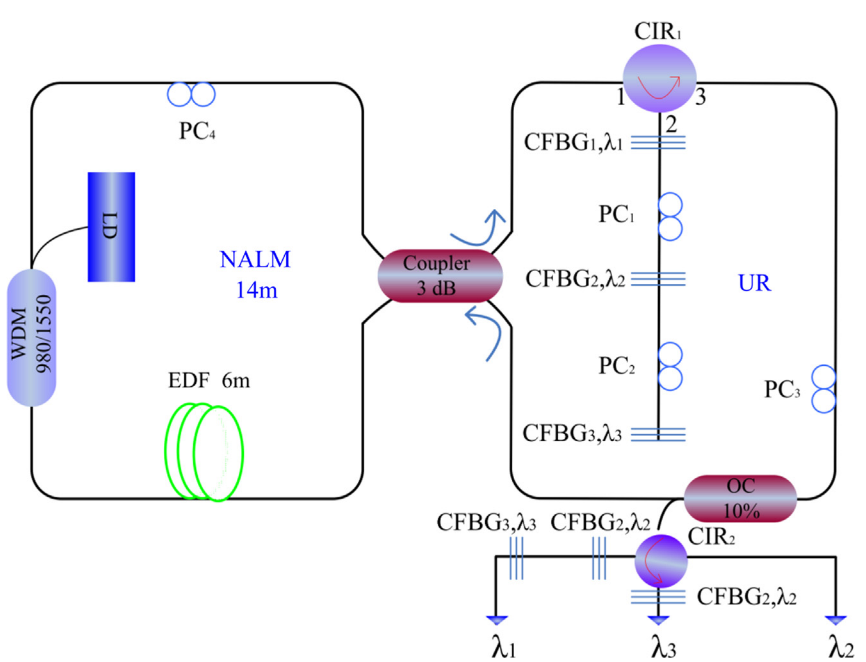

Fig. 1. Experimental setup. EDF: erbium-doped fiber; LD: laser diode; WDM: wavelength-division multiplexer; PC: polarization controller; CIR: circulator; CFBG: chirped fiber Bragg grating; OC: optical coupler.