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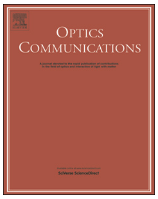

Observation of the evolution of mode-locked solitons in different dispersion regimes of fiber lasers

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ABSTRACT

An all-fiber laser of mode-locked solitons based on the nonlinear polarization rotation (NPR) is proposed with a simple fiber ring cavity. The net dispersion of the ring cavity is adjusted by changing lengths of the erbium-doped fiber (EDF) and single mode fibers (SMFs) in the cavity, resulting in three different dispersion regimes: anomalous dispersion, normal dispersion, and near-zero dispersion. With different intracavity dispersions, the proposed laser can deliver the conventional soliton, typical dissipation soliton (DSs). These nonlinear waves show different features, including the spectral shapes and time traces. Especially in the near-zero dispersion cavity, the DS presents the ultra-broad spectral width. The experiment results provide insight into the evolution of mode-locked solitons with the net cavity dispersion in fiber lasers.

1. Introduction

Mode-locked fiber lasers have attracted great interest because of the significant applications in micromaching, generating terahertz, optical communication and medical science [1–3]. Multiple mode-locked mechanisms, including active mode-locking, passive mode-locking, self-mode-locking and synchronously pumped mode-locking, are well developed over the recent years. Among them, the passively mode-locked technique is simple to generate ultrashort pulses. Diverse approaches, such as carbon nanotube techniques [4], semiconductor saturable absorber mirror (SESAM) [5] and nonlinear amplified loop mirror (NALM) [6], acting as saturable absorbers in fiber lasers, are all employed to evolve the passively mode-locked pulse laser. Among them, graphene-based techniques have been employed to obtain the mode-locking subpicosecond pulse [7] and evanescent wave [8]. In addition, nanoscale p-type Bi_2Te_3 topological insulator particles has also been used as a saturable absorber for inducing the passive mode-locking of the erbium-doped fiber laser (EDFL) recently [9]. On the basis of the application of saturable absorbers, weak pulses generated in mode-locked fiber lasers are suppressed, but the strong pulse narrows down and is amplified. Through numerous round trips, a slight saturable absorber can also generate very short pulses. Besides, nonlinear polarization rotation (NPR) as another mode locking technique also has been extensively investigated. Polarization-dependent components (polarization controllers (PCs) and the polarization dependent isolator (PD-ISO)) in the fiber laser cavity, are acting as a saturable absorber. The NPR technique is mainly based on the weak birefringence and the nonlinear optical Kerr effect of optical fibers to generate an artificial saturable absorption effect in fiber lasers [10,11]. The generations of various solitons result from a dynamic balance among a few factors of nonlinearity, dispersion, gain and loss [12]. Therefore, such fiber lasers are also a convenient experimental platform for the research of nonlinear waves subject to periodic boundary conditions and dissipative effect. A number of optical fiber components, such as the long single mode fiber (LSMF), dispersion compensation fiber (DCF), photonics crystal fiber (PCF), and grating-based fiber devices, have been employed to manage the net dispersion of the fiber laser cavity to determine the evolution of mode-locked solitons. Multiple soliton-shaping mechanisms have been explored in diverse dispersion systems [13]. The net dispersion of a fiber ring cavity can be designed to operate in the anomalous dispersion regime [14], normal dispersion regime [15], and near-zero dispersion regime [16]. Whatever it takes, for a reasonable mode-locked fiber laser, NPR is employed to generate different output soliton pulses with appropriate intracavity dispersion management, the linear polarization and nonlinear polarization. Extensive researches have shown that dispersion management plays a crucial role on the solitons formation in fiber lasers. Aguergaray et al. have explored the characteristics of a wide variety of dissipative solutions generated in an all-normal-dispersion polarization-maintaining

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fiber laser [17]. Recently, Wang et al. investigated the generation of mode-locked rectangular pulses operating in an erbium-doped figure-eight fiber laser with net anomalous dispersion [18]. Additionally, Mao et al. reported pulse trapping in passively mode-locked fiber lasers operating in a near-zero dispersion regime [16]. Nevertheless, to some extent the comprehensive experimental observation of the evolution of mode-locked solitons is deficient in different dispersion regimes. As the net dispersion changes in the fiber ring cavity, we have a clear understanding of the performance of a variety of mode-locked solitons.

In this paper, an all-fiber laser of mode-locked solitons by NPR is proposed and provides four soliton-shapes in three dispersion cavities. The net dispersion of our laser ring cavity is determined by the length of EDF and SMF. In the anomalous dispersion regime, a stable conventional soliton is obtained with symmetrical sidebands. The sidebands will influence the stability of the soliton pulse, which can be effectively weakened by properly rotating the PC. In the normal dispersion cavity, two dissipation solitons (DSs) are generated with different spectral shapes (a rectangular spectrum and a trapezoid spectrum), which can convert to each other by adjusting the PC. When the net dispersion of the ring cavity is close to zero, another DS is achieved with an ultra-broad spectral width. It is observed that mode-locked solitons in fiber lasers are abundantly expressed on the continuous variation of the cavity dispersion.

2. Experiment setup

The schematic diagram of the passively mode-locked soliton fiber laser is shown in Fig. 1. It is composed of a 980 nm laser diode with maximum output power of 520 mw, a 980/1550 nm wavelength division multiplexer (WDM), an erbium doped fiber (EDF) with normal dispersion of about −16.25 ps/nm km, a polarization controller (PC), a polarization-dependent isolator and an optical coupler (OC) with 20% output. These components are connected by the traditional single mode fiber (SMF) with anomalous dispersion of about 16.296 ps/nm km. The pump laser launches the light through the WDM to excite the EDF. Unidirectional propagation and polarization selectivity are managed by the PD-ISO. The PC is employed to control polarization states of the circulating laser in the cavity and introduce a phase difference (linear phase delay bias) between the two orthogonal polarizations. The PD-ISO combining with the single PC forms the NPR mechanism to promote mode-locked operation, inducing an intensity-dependent transmittance loss to generate the fast artificial saturable absorber effect to modulate both the leading and trailing edges of the soliton pulse, which relies on the intensity-dependent rotation of an elliptical polarization state in fibers [19]. Finally, the laser output is monitored concurrently by an optical spectrum analyzer (OSA) (Yokogawa) with 0.02 nm wavelength resolution, a 500 MHZ oscilloscope (Agilent DSO7052A), a radio frequency (RF) analyzer (Anritsu MS272C), a commercial autocorrelator (Femtochrome FR-103WS) and a 1.5 GHz photodetector (Thorlabs SIR5-FC).

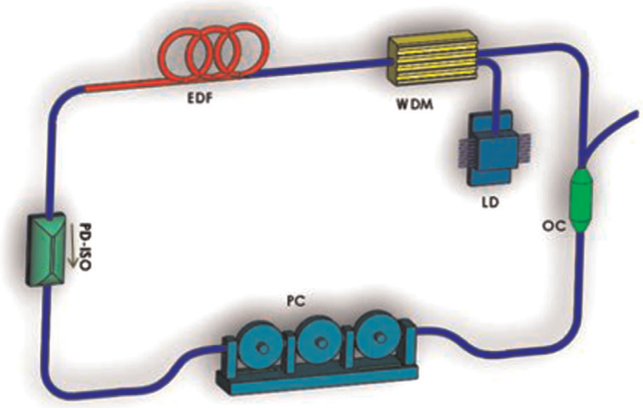

Fig. 1. Schematic diagram of a passively mode-locked soliton fiber laser based on NPR.

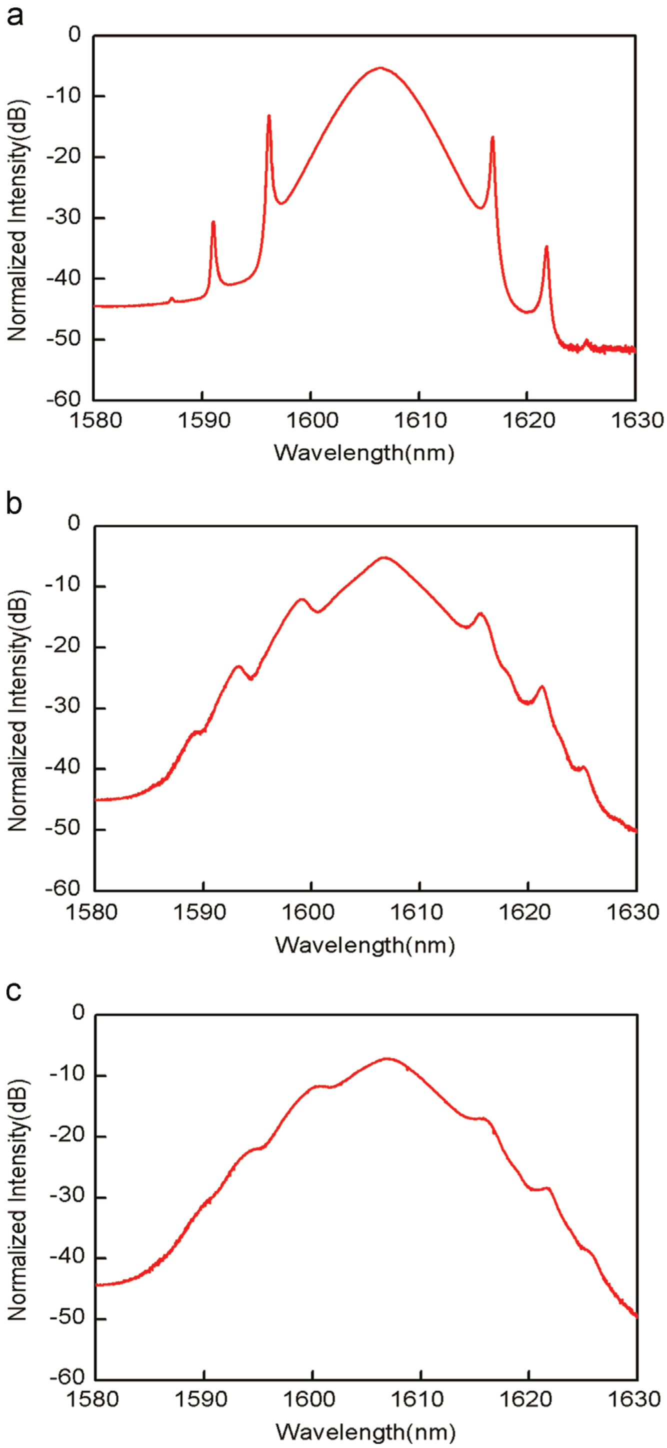

Fig. 2. The evolution of sidebands of optical pulse spectra in different PC orientations. (For interpretation of the references to color in this figure the reader is referred to the web version of this article).

The net dispersion of the ring cavity is determined by the lengths of the EDF and SMFs in the cavity. When the lengths of the