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Observation of bound states of solitons in an L-band passive mode-locking ring fiber laser

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ABSTRACT

We have experimentally observed a single-pulse soliton in an L-band passive mode-locking ring fiber laser, and have observed a weak filter which arose from the balance between the nonlinear phase shift and the gain dispersion. Different bound states of solitons have also been obtained only by carefully adjusting the polarization controller in the cavity. To the best of our knowledge, this is the first time that bound states of the solitons were observed in the L-band fiber laser mode-locked with nonlinear polarization rotation.

1. Introduction

Mode-locked fiber lasers have attracted great attention because of their practical advantages, such as compactness, low cost, robustness and efficient heat dissipation [1]. Recently, with the increasing requirements of the optical communication system and particularly because L-band (1565–1625 nm) lasers have better gain flattening feature than C-band (1530–1565 nm) lasers, researchers have paid more attention to the long wavelength (L-band) lasers [2]. By using a tunable-ratio optical coupler to adjust the wavelength dependent intra-cavity loss, Lin and Chang have realized an actively mode-locked L-band laser with wavelength-tunable femtosecond pulses [3]. Using carbon nanotubes as a saturable absorber (SA), Sun et al. have obtained an L-band passively mode-locked ultrafast fiber laser [2]. In addition, using a semiconductor optical amplifier (SOA) as a loss modulator and a Fabry–Perot semiconductor optical amplifier (FP-SOA) as a tunable comb filter, a multi-wavelength L-band mode-locked fiber ring laser has also been reported [4].

Apart from single pulse mode-locked or continuous wave L-band fiber lasers, another operation state of mode-locked fiber lasers—bound states of solitons have also been observed. Malomed has predicted the formation of bound states of solitons in the coupled nonlinear Schrodinger equations [5] and the quintic complex Ginzburg–Landau equation [6], he has also pointed out that the stable pulse pairs had a fixed phase difference of 0 or π. The existence of bound states of solitons with a $\pi/2$ phase difference has been theoretically predicted [7]. Recently, Zavyalov et al. have theoretically predicted the existence of bound solitons with independently varying phase [8]. The experimentally observed bound states of solitons in a fiber laser have also been reported [9]. Seong and Kim have experimentally obtained bound states of single-pulse solitons in a figure-eight fiber laser [10]. Ortac et al. have reported the generation of high-power bound states of three pulses and the self-similar bound state pulses propagation in ytterbium-doped double-clad fiber lasers [11,12]. Tang et al. have observed bound-soliton pairs and trains of bound-soliton pairs emitting in Er-doped fiber ring lasers[13–15], and suggested that formation of the bound states might be resulted from the direct interactions of solitons, rather than joint action with the resonant dispersive-wave [16,17]. Haboucha et al. have experimentally observed the bound states of 350 pulses in an Er/Yb doped double-clad fiber laser [18] and investigated the quantization of bound solitons [19]. However, to the best of our knowledge, no bound states of two solitons have been observed in an L-band passively mode-locked Er-doped fiber laser.

In this paper, we have reported the observation of bound states pulses in an L-band Er-doped fiber laser. At a fixed pumping power, bound states of two solitons with different separations could be obtained only by adjusting the polarization controllers (PCs) in the cavity. Moreover, we have also obtained the bound states of twin-pulse solitons and the bound states of three soliton pulses.

2. Experimental setup

The schematic of the fiber laser was shown in Fig. 1. The cavity consisted of a 2.65 m long high doping concentration erbium-doped fiber (HDCEDF) with a group velocity dispersion (GVD) of −52

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(ps/nm)/km, which was able to supply sufficient gain for laser operation in L-band. A 980/1550 nm wavelength division multiplexer (WDM) was inserted to launch the pump light into the ring cavity. The output pulses were extracted via a 10% fiber output coupler. The nonlinear polarization rotation (NPR) technique was used to achieve self-starting mode-locked operation. A polarization-dependent isolator (PDISO) and two fiber squeezer PCs were used as the mode-locking component in the cavity. The PDISO also ensured that the light was unidirectional during circulating operation. The pump source was a 980 nm laser diode (LD) with a maximum output power of ~254 mW. The total cavity length of 12.6 m included 9.95 m standard single mode fiber (SMF) with a dispersion of 18 (ps/nm)/km and the net cavity dispersion was approximately −0.05 ps^2. An optical spectrum analyzer (Yokogawa AQ6317C), a 1 GHz sampling oscilloscope (Yokogawa DL9140) with a photo-detector and a commercial optical autocorrelator (FP-103XL Autocorrelator) were used to monitor the spectra, the oscilloscope trace and the pulse width simultaneously.

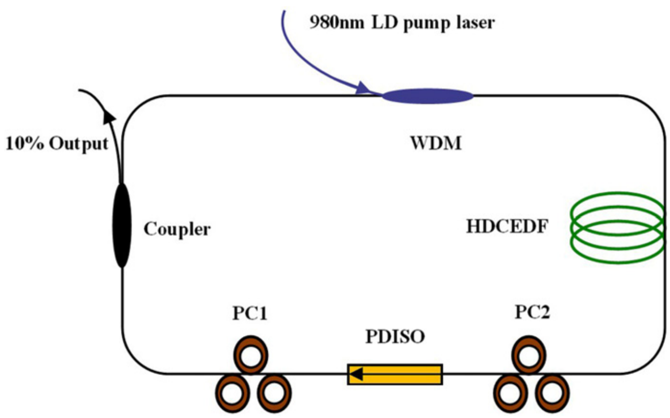

Fig. 1. Schematic of the fiber laser. WDM–980/1550 nm wavelength division multiplexer; HDCEDF–high doping concentration Erbium-doped fiber; PDISO–polarization dependent isolator; PC1, PC2–fiber squeezer polarization controller.

3. Experimental results and discussions

Self-starting mode-locked operation was easily initiated when the pumping power was increased beyond the mode-locking threshold and the orientations of the PCs in the cavity were appropriately adjusted. When the pumping power was 36.6 mW, pulse train of single pulse was observed as shown in Fig. 2. Fig. 2(a)–(c) showed the spectrum, the autocorrelation trace and the oscillogram of an output single pulse, respectively. The central wavelength was about 1605.5 nm and the 3 dB bandwidth was 10.45 nm. The full width at half maximum (FWHM) of the pulse was 2.63 ps if a Gaussian-shape pulse (dotted line denoted the Gaussian-fit curve) was assumed. The output pulse had significant chirp of ~3.2. The fundamental repetition rate was ~15.9 MHz, which corresponded to the cavity length very well.

In our experiment, the gain medium was the HDCEDF, and its length of 2.65 m was more than enough to completely absorb the pumping power, thus there was an un-pumped section of the HDCEDF. Using ASE obtained from the pumped part as a secondary pump source, we could obtain the gain shifting toward the L-band. The central wavelength of the soliton could be tuned, but regretfully the tunable range was small.

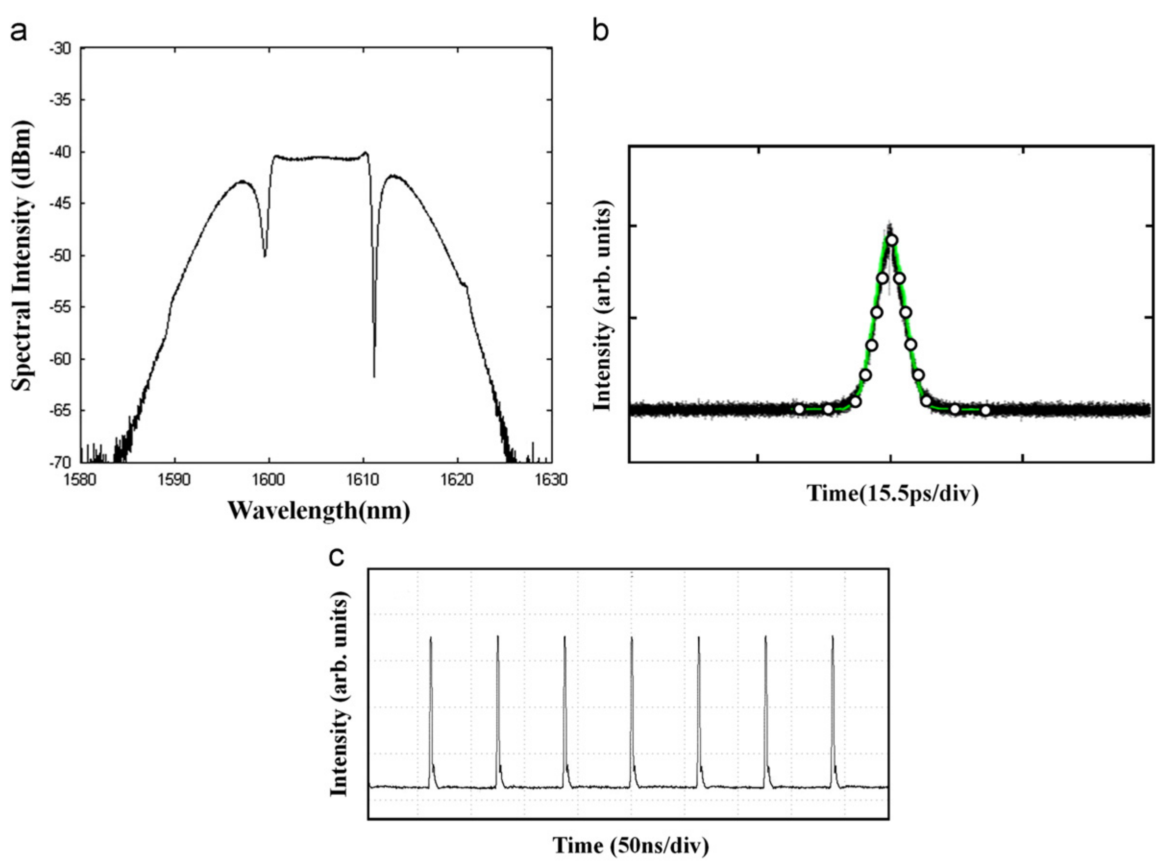

Fig. 2. A typical single pulse exported from our laser. (a) optical spectrum; (b) the corresponding autocorrelation trace (solid line) and Gaussian-form profile (dotted line); (c) the oscilloscope trace of the pulse train.