Complex soliton patterns formation in a multi-wavelength Er-doped fiber laser

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Abstract. We report on the emission of complex soliton patterns from a multi-wavelength mode-locked Er-doped fiber laser through nonlinear polarization rotation (NPR). The optical spectrum exhibits three distinct well-separated spectral peaks centred at 1567 nm, 1585 nm, and 1616 nm. It is mainly attributed to the linear losses and the nonlinear birefringence filtering inside the cavity. Each wavelength in the spectrum contributes by its own soliton dynamics to a composite-state soliton regime. This is verified by using an external optical tunable filter with 0.5 nm filter bandwidth to filter out the lasing at each wavelength. By controlling the cavity parameters, this regime still can be operated in harmonic states.

1. Introduction
The development of complex soliton patterns within passively mode-locked fiber laser has stimulated a great interest in investigating new laser technologies. It could be used in many applications such as spectroscopy, biomedical diagnostics, surgery of the cornea, and so on. The multiple pulsing occurs from an excess of nonlinear phase shift per roundtrip. In anomalous dispersion regime, the pulse energy is limited by the soliton area theorem while in normal dispersion regime it is the nonlinear losses coupled with the finite gain bandwidth. Consequently, in both regimes the complex soliton patterns arise. Passively mode-locked fiber lasers with several hundreds coexisting pulses have been generated, especially in the anomalous dispersion [1]. Various passive mode locking techniques are used, such as the nonlinear loop mirror-based method [2], and the nonlinear polarization rotation (NPR) technique [3].

By manipulating the laser cavity parameters, the coexistence of chaotic and regular soliton structure in fiber lasers has been theoretically predicted [4]. Tang et al. investigated experimentally the coexistence of two types of soliton shape based on dispersion management in near zero dispersion regime [5]. Afterwards, Wang reported on the coexistence of bright pulses and dark solitons in Er-doped fiber laser (EDFL) with strong normal cavity dispersion [6]. Moreover, different soliton patterns inside the same signal can simultaneously coexist. In Ref [7], the coexistence of alternate crystal and liquid soliton phases was experimentally observed. Meanwhile, in an ultra-large net anomalous dispersion EDFL, the demonstration of the coexistence of strong and weak pulses has been reported [8]. In addition, the simultaneous generation of harmonic soliton molecules with rectangular noise-like pulses and the coexistence of high repetition rate harmonic mode-locking with noise-like pulse have been demonstrated [9, 10]. In 2018, the coexistence of dissipative soliton and stretched pulse was also observed in a dual-wavelength Tm-doped fiber laser [11]. Very recently, the emission of multi-state solitons (soliton singlets and molecules) in a dual-wavelength EDFL laser has been reported by Liu et al. [12]. All these works were carried out in lasers operating with single or dual-lobe wavelength.

In this work we present experimental results of new dynamics of complex soliton patterns formed from a three distinct wavelength-lobe.
2. Experimental setup of complex soliton patterns

The experimental setup of the laser cavity is shown in Fig. 1. It is an all-fibered unidirectional ring cavity. It comprises a C-band Er:Yb co-doped double-clad fiber amplifier, two polarization controllers (PC1 and PC2), a polarization-dependent isolator (PD-ISO), a 10% coupler (OC 10%), and an additional single-mode fiber (SMF) coil. The length of the cavity is about 304 m, with 5 m of double-clad fiber and 299 m of SMF making the total net cavity dispersion of -6.683 ps². The mode-locking operation is achieved through the nonlinear polarization rotation (NPR) mechanism. The desired multi-lobe wavelength regime is obtained by exploiting the length of the cavity and the nonlinear filtering [12-14]. Also, the management of the intracavity losses allows wavelength generation in the L-band [15]. The acquisition system used to analyze the output signal consists of an optical spectrum analyzer, a 13-GHz oscilloscope combined with two 12-GHz photo-detectors, and an electronic spectrum analyzer. Wavelength-resolved measurements are performed at the output of the cavity with an optical tunable filter (OTF) with a spectral bandwidth of 0.5 nm and a tuning range from 1500 to 1630 nm.

3. Experimental observations and discussion

With an appropriate adjustment of the polarization controllers and after the stabilization of the cavity, a self-started mode-locking occurs. Figure 2(a) represents the optical spectrum. At the starting pump power of 0.27 W, the spectrum exhibits two separate wavelengths. The first one, operating at 1567 nm, is associated with a continuous wave and the second one operating at 1585 nm is associated with a soliton operation. The corresponding temporal trace is shown in Fig. 2(b) with a black curve that displays narrow square shape soliton clusters. By carefully increasing the pump power, a third wavelength started to grow at 0.37 W to finally achieve a triple-wavelength operation with three distinct spectral lobes located at ~1567 nm, ~1585 nm, and ~1616 nm, leading to coexisting soliton patterns as observed on the temporal trace. Such spectrum dynamics are essentially attributed to the high birefringence of the cavity together with the population inversion related to the linear intracavity losses which enhance lasing at longer wavelengths.

To study the contribution of each lobe, a wavelength filtering is performed with an OTF. The temporal trace of the wavelength resolved signals, measured at the pump power of 0.8 W, are depicted in Fig. 3. The pink curve represents the whole signal with no filtering and stays as a reference. The black curve represents the signal corresponding to the wavelength lobe located at 1567 nm and it is a non-resolved bunch of solitons. The red and blue curves, corresponding to the wavelength lobes located at 1585 nm and 1616 nm respectively, are both square condensed phase solitons, propagating at the same group velocity. Indeed, as the two pulse trains have separated wavelengths, they are supposed to have different group velocities because of the group velocity dispersion of the cavity, thus giving a different fundamental repetition frequency [16], but it is not the case in our result. This indicates that the two pulse trains are group velocity locked.
As the optical spectrum evolved from dual-wavelength to triple-wavelength operation, an additional investigation of the effect of the pump power on this regime is made. By increasing the pump power from 1.67 W to 3.25 W, the regime is still stable. Figure 4(a) shows a quite similar spectrum evolution to that of Fig. 2(a) versus the pump power. The corresponding temporal trace, represented in Fig. 4(b), shows a spread of the soliton bunch over the cavity associated with an increase of the width of the square condensed phase solitons. When the pump power is increased to 4.01 W, the spectrum of the shortest wavelength became smooth. We can also note that the temporal trace of the soliton bunch continued to spread until forming a high repetition rate harmonic of narrow soliton bunches at a period of 7.16 ns as depicted in the inset of Fig. 4(b), and the duration of the square pulse is reduced. The RF spectrum of this regime, measured at the pump power of 4.01 W, is presented in Fig. 5. The peak at 656.4 kHz represents the fundamental repetition rate of the cavity and attests to the good stability of the regime with a signal-to-noise ratio (SNR) of 62 dB. The inset of Fig. 5 illustrates the RF signal envelope with a span of 250 MHz. It allows seeing the frequency peak at 139.5 MHz corresponding to the repetition frequency of the high repetition rate harmonic pulses of the soliton centered at 1567 nm.
Figure 4. (a) Evolution of the spectrum versus the pump power, and (b) the corresponding temporal traces.

Figure 5. Radio frequency spectrum at the pump power of 4 W. Inset: RF spectrum measured with 250 MHz span.

Additionally, by fine modification of the PCs position, harmonic states of the studied triple-wavelength regime can occur. The optical spectra and the corresponding temporal traces of different harmonic orders at the pump power of 3.2 W are shown in Fig. 6(a) and Fig. 6(b). Their periods are ~770 ns, ~378 ns, and ~189 ns, representing the 2nd harmonic, 4th harmonic, and 8th harmonic, respectively.
Figure 6. Optical Spectra (a) and oscilloscope traces (b) of harmonic complex soliton patterns at the pump power of 3.2 W.

4. Conclusions
To conclude, we have experimentally demonstrated a triple-wavelength mode-locked EDFL based on the NPR technique, showing the coexistence of complex soliton patterns. The spectrum consists of three distinct wavelengths centered at 1567 nm, 1585 nm, and 1616 nm. By performing wavelength resolved measurements using an optical tunable filter, we observed that each soliton pattern corresponds to one different wavelength. By a fine adjustment of the PCs position, the studied regime can switch into different harmonic states. This work shows a novel operation regime, which might help to understand the complex mode-locking soliton dynamics and the multiwavelength generation, which is very useful for many applications, particularly in wavelength division multiplexing (WDM) transmission systems.

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