Manipulation of large soliton ensembles in Er-doped double-clad fiber laser

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Abstract: We have studied the influence of an external continuous wave on a passively mode-locked fiber laser operating in the soliton regime. Starting from an irregular soliton distribution it is shown that harmonic mode-locking is obtained.
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1. Introduction

Passively mode-locked high power fiber laser operating in the anomalous dispersion regime are well adapted for the generation of multi-soliton states. In general, the number of solitons increases when the pumping power grows as a consequence of quantization of the soliton energy. Many different soliton patterns have been reported independently of the exact mode-locking mechanism revealing some universal properties [1]. The resulting solitons distribution in fiber laser is a direct consequence of their interactions which can be repulsive or attractive or both at different scales. Attractive interaction is responsible of bound states [2] or soliton crystals [3]. Repulsive interaction is responsible of the well-known harmonic mode-locking (HML) [4]. In many HML fiber lasers, a continuous wave (cw) component is present in the optical spectrum suggesting that this component could play an important role in the HML mechanism [4]. It has been recently shown theoretically that a small cw component allows to control the nature and the strength of the soliton interaction [5]. Based on this prediction and on the role of the cw component in the HML, we have decided to conduct several series of experiments on a passively mode-locked fiber laser injected with an external cw component. In this communication we demonstrate experimentally for the first time that a passively mode-locked fiber laser can be forced to operate in HML regime by means of an external cw component [6]. Starting from different initial soliton distributions, we show that the external cw component can force the laser to change its operating regime and, under specific injection conditions, the laser operates in the harmonic mode-locking regime. The effect of the injected cw signal is reversible and reproducible. Preliminary theoretical results obtained from a vectorial model are also presented [7].

2. Experimental results

The experiments have been conducted with a 10 W Er:Yb-doped double-clad fiber laser operating in the anomalous dispersion regime. Mode-locking is obtained through nonlinear polarization evolution. The cavity is all-fibered and contains two polarization controllers which allow to modify the nonlinear losses of the cavity. Depending on their orientations, different soliton distributions are obtained involving up to few thousands of individual pulses per cavity round-trip. Figure 1(a) represent the initial soliton distribution. It consists in a set of well separated soliton packets which do not move from one round-trip to the other. Each packet contains a different number of bound solitons and repeat from round-trip to round-trip. The total number of solitons is estimated to be about 1500 and the pulse duration about 1 ps. We then switched on the external laser with a starting wavelength $\lambda_{ext} = 1530\,\text{nm}$ and with an injected power of 110 mW into the principal laser. While λ_{ext} is then tuned towards longer values, the soliton packets become unstable and move and collide to form larger condensate phases without evident internal order, then pulses get loose from the condensate phases and span over the whole cavity, they move like a soliton gas. When $\lambda_{ext} = 1552\,\text{nm}$, solitons are at rest, nearly identical and equidistant as shown in Fig. 1(b) which gives the final temporal distribution of the pulses. The final state corresponds to HML operation of the laser. The repetition rate of the laser is actually 5.82 GHz which corresponds to the 945th harmonics. The supermode suppression ratio is 12 dB. The time jitter and the amplitude fluctuations are important and clearly visible in the zoom of Fig. 1(b). From the data series, the amplitude fluctuations are estimated to be about 18 %. We have verified that the phenomena is reversible.

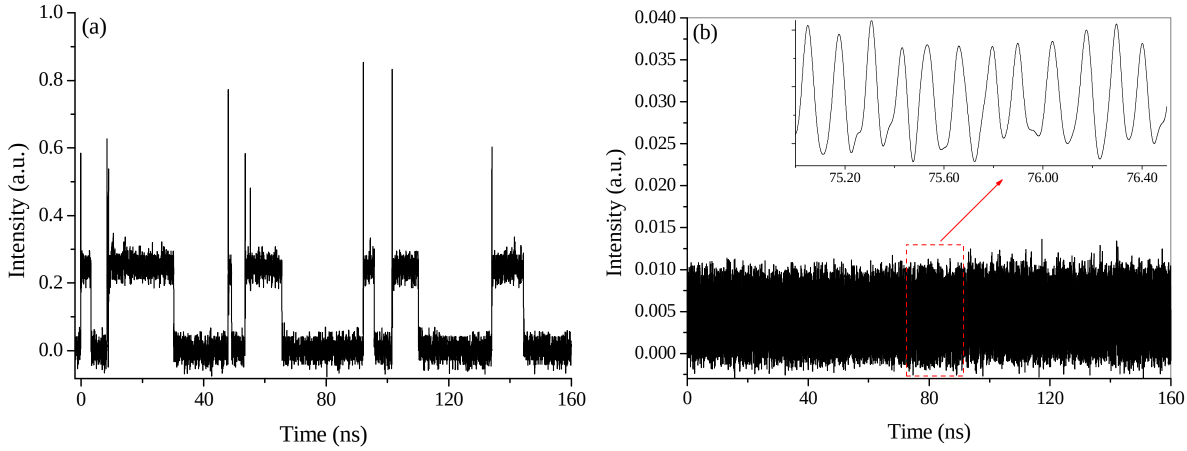

Fig. 1. (a) Initial and (b) final soliton distributions.

3. Theoretical results

To develop our analysis of the role of an external optical injection on the interaction between solitons in a fiber laser with the nonlinear polarization rotation technique, we use the vectorial model described by the following normalized equations for the two electric field components [7]:

$$\frac{\partial E_x}{\partial \zeta} = (D_r + iD_i)\frac{\partial^2 E_x}{\partial \tau^2} + gE_x + iq\left(\left|E_x\right|^2 E_x + A\left|E_y\right|^2 E_x + BE_y^2 E_x^*\right) + P\exp i\left(\delta\omega\tau - \delta\kappa\zeta\right) \qquad (1)$$

$$\frac{\partial E_y}{\partial \zeta} = (D_r + iD_i)\frac{\partial^2 E_y}{\partial \tau^2} + gE_y + iq\left(\left|E_y\right|^2 E_y + A\left|E_x\right|^2 E_y + BE_x^2 E_y^*\right) \qquad (2)$$

Numerical simulations show that depending on the value of its intensity and its frequency, the external wave can induce a repulsive or an attractive interaction between solitons. As a consequence, the laser operates in bound solitons or harmonic mode-locking regimes, respectively.

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