Passive mode-locking of a 10 W double-clad fiber laser

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ABSTRACT

We report experimental observation of bound states of soliton in passively mode-locked erbium-doped double-clad fiber laser. Operating in the anomalous dispersion regime with a double-clad fiber 10W amplifier allows generation of up to several thousands of solitons per round trip. By increasing the pumping power we pass from one bound state to several separated bound states. The bound states self-organize them leading to harmonic mode-locking of soliton crystals.

Keywords: soliton, passive mode locked laser, harmonic mode lock, solitons crystal.

1. INTRODUCTION

Passively mode-locked fiber lasers have demonstrated that they are very good candidates for the investigation of both the generation and the interaction of ultrashort pulses and they have demonstrated their great ability to generate a large number of pulses up to several hundred, especially in the anomalous dispersion regime [1-6]. A bound state of solitons consists in several identical pulses close together in one package, which are equidistant and have a fixed phase relation. The study of such states was initiated in 1991 by Malomed [7]. Akhmediev et al. found theoretically stable soliton pairs and trains within the Ginzburg–Landau equation [8]. Tang et al. reported in 2001 the experimental observation of a stable bound state of two solitons separated by 1.6 ps [9]. The scaling up of the power in fiber lasers has recently permitted the experimental observation of a bound state of hundreds of solitons, a stable crystal of 350 solitons [1]. On the other hand, among the different hypotheses proposed to explain the formation of the HML [10,11], it seems that the interaction of pulses through a cw component is responsible for high-order HML [12,13]. In addition, it has been recently demonstrated that a small cw component in the spectrum enables one to control the sign and the amplitude of the soliton interaction [14]. Tang et al. reported the experimental observation of passive HML of soliton bunches and twin-pulse solitons in a passively mode-locked fiber ring laser [15]. Kutz et al. studied the effects of the gain depletion and recovery on the temporal spacing of the soliton pulses. They have shown that gain depletion in conjunction with its recovery provides an effective repulsive force between adjacent solitons by imparting a group velocity drift proportional to the inter-pulse spacing [10]. In this paper we present the observation both behaviours at the same time. Indeed we report the harmonic distribution of bound states, where 50 bound states are evenly distributed along the cavity. At low pumping level, we observe one bound state with ~ 600 pulses. By increasing the pumping power, the number of pulses increases in the bound state to ~ 900 pulses. After, with increasing the pump power, several bound states separate from the initial bound state and progressively occupy the cavity, and finally form an harmonic mode locking regime of bound states [17].

2. EXPERIMENTAL SETUP

The experimental setup is schematically represented in Fig. 1. It is an all-fiber unidirectional ring cavity. Mode locking is achieved through nonlinear polarization rotation technique. We use a double-clad Er:Yb fiber amplifier manufactured by Keopsys, which consists of a 5m long double-clad fiber (DCF) that has a chromatic dispersion coefficient $\beta_2^{DCF} = -0.021\,ps^2/m$ at the operating wavelength $\lambda = 1.55\ \mu m$, and is pumped at 980nm by laser diodes emitting about 40 W. The fibers DCF and SMF28 exhibit anomalous dispersion. A piece of dispersion-shifted fiber ($DSF, \beta_2^{DSF} = 0.14\,ps^2/m$) is added to control the total cavity dispersion. To favor multiple-pulse mode locking, the total dispersion is set in the anomalous regime with $\beta_2^{TOT} \times L \approx -0.12\,ps^2$. A total cavity length is 30.5 m corresponding to a round trip time of 152.9 ns. An auxiliary laser is recorded by a coupler 50/50 to the principal cavity to start up of the amplifier with a signal of 17 dBm (we can turn-off after starting the amplifier). A polarizer isolator is set between two polarization controllers and mode locking is obtained through the adjustment of the polarization controllers. The output intensity is detected with a high-speed photodetector (TIA-1200) and visualized with a fast oscilloscope (Tektronix TDS 6124C, 12 GHz, 40 GS/s). The spectral properties are analyzed with an optical spectrum analyzer (Anritsu MS 9710C) and the pulse duration is measured with an optical autocorrelator with a scanning range of ±100 ps (Femtochrome FR-103 XL).

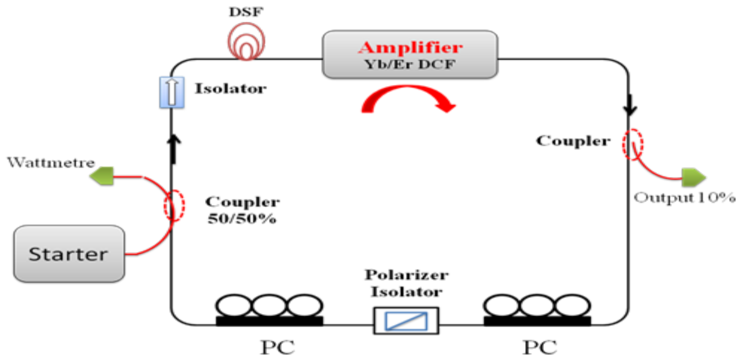

Figure 1. Experimental setup. DCF, double-clad fiber; DSF, dispersion shifted fiber; PC, polarizer controller. Starter, auxiliary laser to start up of the amplifier.

3. RESULT AND DISCUSSION

When the laser operates at low level, at 10 W pumping level (2 W intracavity at 1.55 µm) and adjusting the polarization controllers, a condensate state is formed: it consists in a large number of regularly spaced identical solitons with constant relative phase differences from one round trip to the next. It is a soliton crystal of several hundreds of solitons [1]. The soliton train spans over 6.6 ns, as indicated by the temporal intensity recorded in Fig. 2a. The corresponding optical spectrum given in Fig. 2b proves the strong coherence between pulses since it is modulated with a contrast exceeding 95%. The spectral period is 0.83 nm, which corresponds to a temporal separation of ~10 ps between solitons, in good agreement with the autocorrelation trace shown in Fig. 2c. From the train duration and the delay between solitons, we estimate the number of pulses in the soliton crystal to be 660 pulses. By increasing the pump power to 15W (4 W intracavity at 1.55 µm), the length of the crystal begins to increase, it broadens from 6.6 ns to 9 ns (Fig. 3a). The optical spectrum with strong modulation (Fig. 3b) and the autocorrelation trace with a large number of regularly spaced identical pulses (Fig. 3c) confirm that it is a soliton crystal of several hundreds of solitons. The temporal separation between pulses is the same and it does

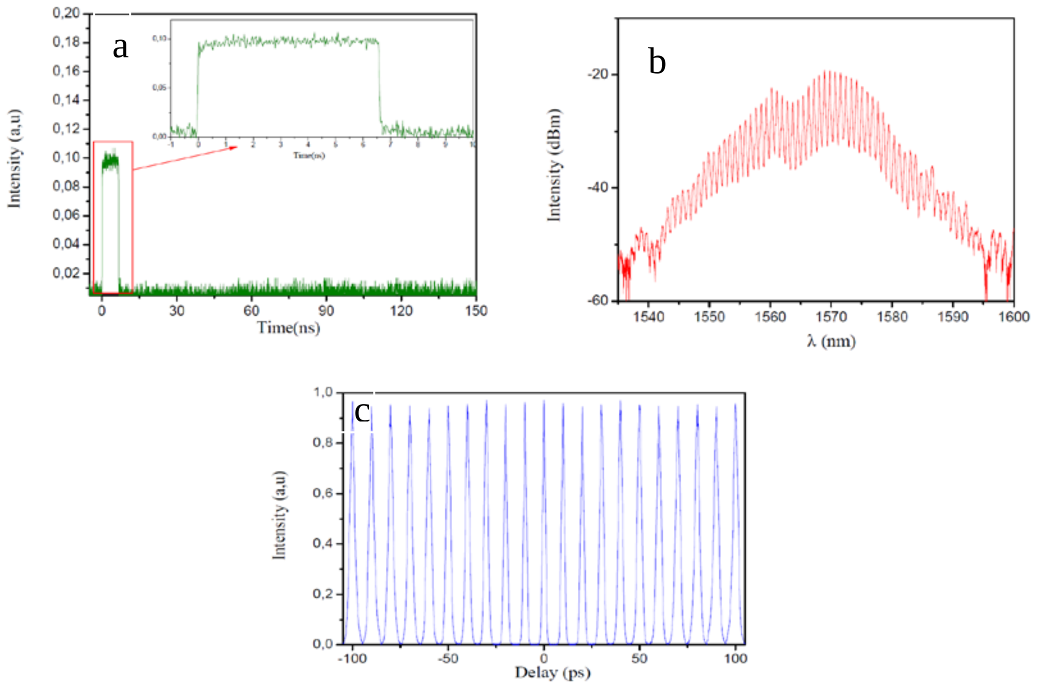

Figure 2. a) Temporal trace of a soliton crystal of 6.6 ns at 10W pumping power, b) Optical spectrum,

c) Autocorrelation trace.

not change during the increase of pumping power. We estimate the number of pulses in the soliton crystal to be 900 pulses, which is actually a record in comparison to our previous works [1-3]. The increase of the number of pulses in the crystal results from the growth of the pumping power as it was theoretically predicted [18]. By increasing slowly the pump power up to 25 W (6.3 W intracavity at 1.55 µm), several soliton packets begin to become loose from the initial soliton crystal. Simultaneously, a cw component appears in the optical spectrum. We expect that the cw component introduces a repulsive force between solitons. The inset in Fig. 4a reveals that the packets are uniformly distributed and that all packets have the same time duration. Each packet is a bound state as demonstrated by the strongly modulated optical spectrum of Fig. 4b.

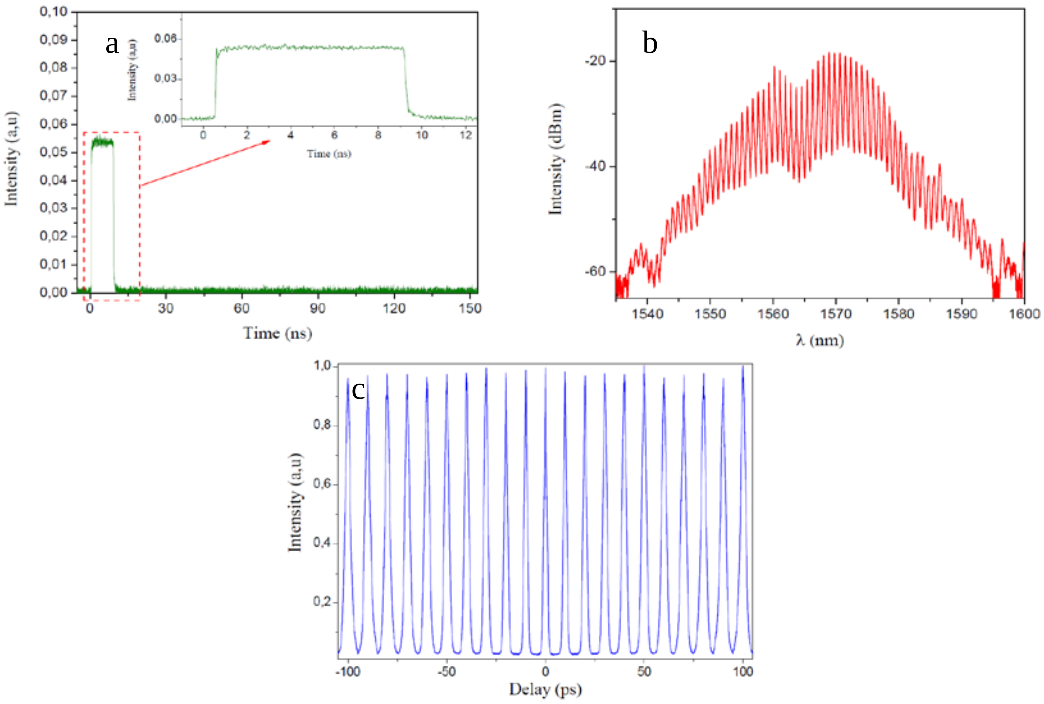

Figure 3. a) Temporal trace of a soliton crystal of 9 ns at 15W pumping power, b) Optical spectrum,

c) Autocorrelation trace.

The spectral period is 0.82 nm, resulting in a delay between solitons inside the bound state of 10 ps, as confirmed by the autocorrelation trace shown in Fig. 4c. We note that the envelope of the autocorrelation trace is nearly triangular, which proves that the solitons are identical inside a packet. From the delay and the duration of a bound state, we estimate the number of solitons inside a bound state to be about 50.

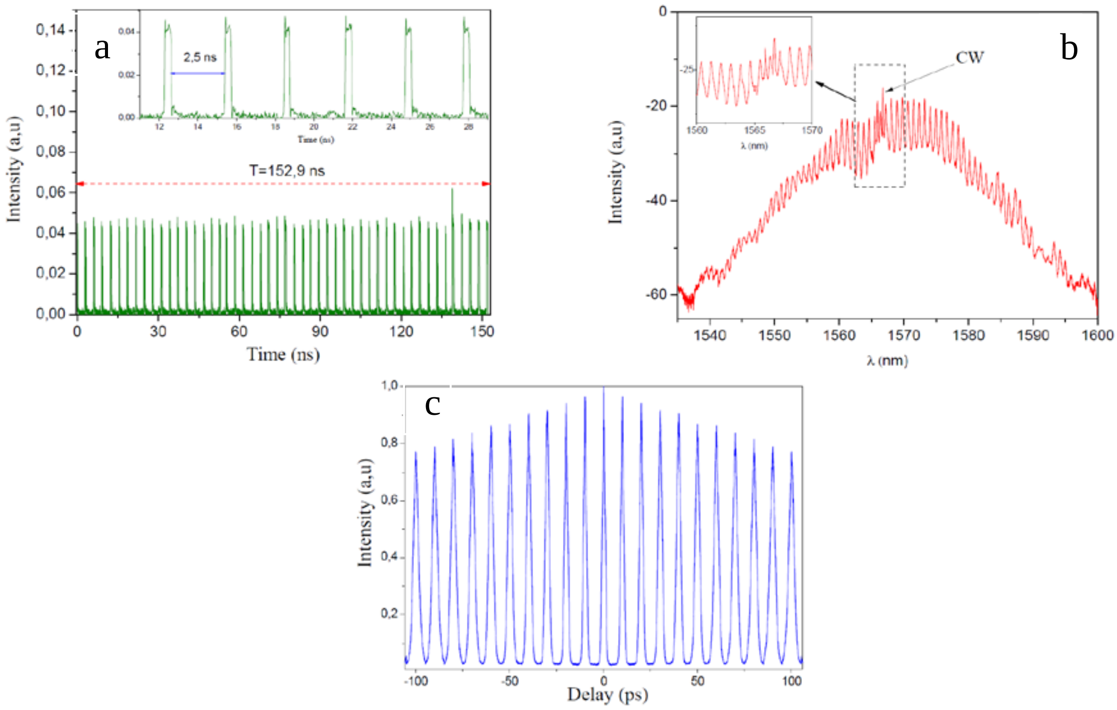

Figure 4. a) Temporal trace of HML of solitons crystal at 25W pumping power, b) Optical spectrum of HML of solitons crystal, c) Autocorrelation trace of HML of solitons crystal.

The bound state is therefore a soliton crystal containing only a small part of the total soliton set. We obtain finally the fiftieth harmonic of soliton crystals containing about 50 solitons. The total number of solitons is therefore about 2500. Inspecting of the optical spectrum reveals two remarks. First, the modulation characterizes the bound state, and, second, the HML is correlated with the existence of a cw component visible in the optical spectrum as it was previously indicated [17]. The HML state is stable over 1 h and is reproducible. The radiofrequency spectrum calculated by the Fourier transform of the temporal trace reveals that the repetition rate is about 330 MHz and that supermode suppression is better than 15 dB. Compared with the fundamental cavity frequency 6.53 MHz, it proves the generation of the fiftieth harmonic. The timing jitter between crystals is deduced from the histogram of the corresponding delays; the timing jitter is about 200 ps. Their amplitude fluctuation, about 10%, is deduced from the temporal trace. The pulse to pulse timing jitter inside a crystal can be estimated from the broadening of the peaks of the autocorrelation trace from the centre to the edge. It is less than 0.4 ps.

4. CONCLUSIONS

In summary we have experimentally demonstrated the HML of soliton crystals in an Er-doped DCF laser mode locked by NLPR. The formation dynamics is obtained by increasing the pumping power, the initial soliton crystal splits into several identical soliton crystals of smaller extent. The splinters rearrange their relative positions in the cavity and then form the harmonically mode-locked state. The existence of a cw component has been pointed out and is in agreement with previous experimental observation.

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