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Harmonic mode-locking in a fiber laser through continuous external optical injection

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ABSTRACT

The effect of an external continuous wave (cw) on the operating regime of a passively mode-locked double-clad fiber laser, operating in the anomalous dispersion regime, is experimentally investigated. Starting from different soliton distributions, we demonstrate that, under specific conditions, the cw signal forces the principal laser to operate in harmonic mode-locking regime. This effect is fully reversible and does not exhibit any hysteresis phenomena.

1. Introduction

Soliton interaction has now a long history since the initial papers in the middle 80s which concerned conservative solitons [1,2]. With the emergence of fiber lasers, and in particular double-clad fiber lasers, there was a revival on soliton interaction in the framework of dissipative solitons [3–8]. Indeed, in passively mode-locked high power fiber laser, a large number of solitons can coexist in the cavity when operating in the anomalous dispersion regime. As a general rule, the number of solitons in passively mode-locked fiber lasers increases when the pumping power grows [9–11]. Many different soliton patterns have been reported independently of the exact mode-locking mechanism revealing some universal properties [12–17]. 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 [5,18,19] or soliton crystals [20,21]. Repulsive interaction is responsible of the well-known harmonic mode-locking (HML) [22]. 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 [23–26]. Finally, one can note that although it is possible to easily generate different soliton patterns in a fiber laser by adjusting some external control parameter (in general it is a waveplate, a fibered polarization controller or merely the pumping power), a total control of the final distribution is not possible. Indeed the latter is reached after some evolution started from noise, and generally depends on it, which is random. This differs from the evolution of pulses in an amplifier, and of several theoretical approaches in which suitable initial data are chosen to obtain a desired soliton distribution. It has been recently shown theoretically that a small cw component allows controlling the nature and the strength of the soliton interaction [27]. 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. To be complete it is worth to mention that a first attempt to investigate the role of an external cw component on a passively mode-locked fiber laser has been done in [28]. The authors demonstrated that the external laser allows forcing the principal laser to generate a rain of solitons. However, this control has low interest for practical applications.

In this paper 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. Starting from different initial soliton distributions, we show that (i) the external cw component can force the laser to change its operating regime, (ii) under specific injection conditions the laser operates in the harmonic mode-locking regime and (iii) the effect of the injected cw signal is reversible and reproducible. In Section 2 we describe the experimental setup. The experimental results are presented in Section 3.

2. Experimental setup

The experimental setup is schematically represented in Fig. 1 [26]. It is an all-fiber unidirectional ring cavity. Mode locking is

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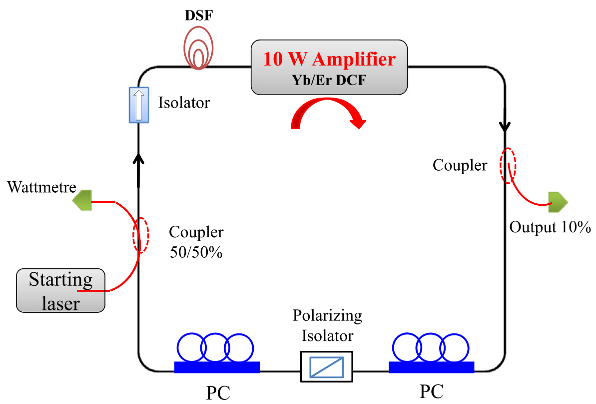

Fig. 1. Experimental setup.

achieved through nonlinear polarization evolution technique. We use a double-clad Er:Yb 10 W fiber amplifier operating at $\lambda = 1.55$ μm manufactured by Keopsys. It consists in a 5 m long double-clad fiber (DCF) that has a group velocity dispersion coefficient $\beta_2^{DCF} = -0.021$ ps^2/m. The geometry of the inner clad has an octagonal shape which allows a high coupling efficiency of the multimode pump waves into the fiber. The diameter of the inner clad is 130 μm and the fiber core diameter is 12 μm. It is pumped at 980 nm with several laser diodes injected with the v-groove technique. The maximum available pumping power is up to 40 W which ensures a total output power of amplified spontaneous emission up to 10 W. This value coincides with the maximum achievable output power in continuous lasing operation. The two fiber ends of the double-clad fiber are spliced to pieces of standard single-mode fibers (SMF28). The fibers DCF and SMF28 operate in the anomalous dispersion regime. A piece of dispersion-shifted fiber ($\beta_2^{DSF} = 0.14$ 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 $\beta_2^{TOT} L = -0.16$ ps^2, with a total cavity length of $L = 32.5$ m corresponding to a round trip time of 162.4 ns and to a free spectral range of 6.16 MHz. Because of internal electronic security to avoid irreversible damages to the 10 W amplifier in the absence of input signal, an external signal must be used to start up the amplifier. The external light is provided by a home-made cw tunable fiber laser [29] and is launched with a 50/50 coupler to the principal cavity with a signal power which can be varied up to 800 mW (400 mW injected in the principal laser cavity). After the principal laser becomes operating, we switch-off the starting laser to avoid any coupling between both lasers. A polarizing isolator is set between two fibered polarization controllers. Mode locking is obtained through the adjustment of the latter. The output intensity is detected with a high-speed photodetector (TIA-1200) and visualized with a fast oscilloscope (Tektronix TDS 6124C, 12 GHz, 40 GSa). 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). An electronic spectrum analyzer (Rohde & Schwarz FSP Spectrum Analyzer 9 kHz to 13.6 GHz) is used to characterize the radio frequency spectrum of the laser. When the principal laser is mode-locked, the spectrum spans from 1540 nm to 1585 nm while the starting laser, which operates in cw regime, is tunable from 1530 nm to 1560 nm. The linewidth of the tunable laser is about 1 nm.

3. Experimental results and discussion

In the following the pumping power of the principal laser has been fixed to 10 W which corresponds to about 2 W of average circulating power at 1.55 μm and to 200 mW of average output power. As usual, the adjustment of the polarization controllers allows to obtain a large variety of soliton distributions [14,15].

For the experiments of injection described in this section, we processed as follows. First the principal laser is switched on by using the starting laser with an injected power level of about 17 dBm (50 mW), and with a wavelength out of the optical spectrum of the principal laser. Then the external laser is switched off and the polarization controllers of the principal laser are adjusted to obtain some soliton pattern. While this pattern is stable, we have switched on the external laser and then increased its wavelength starting from 1530 nm. Its influence on the operating regime of the principal laser is studied. Reversibility of the phenomena is checked in different ways. First the wavelength of the external laser is decreased to retrieve its initial value and secondly, without varying the wavelength we have reduced and then vanished the injected power. In all cases the initial soliton distribution is restored. Let us note that while the wavelength of the external laser is tuned with a fixed output power, the intracavity power of the principal laser does not vary significantly as confirmed by the nearly constant output power. Thus the nonlinear polarization evolution in the fibers, and then the nonlinear filtering, can be considered as slightly affected by the injected laser.

3.1. From bound states to harmonic mode-locking

With a suitable adjustment of the polarization controllers we obtain the soliton pattern represented in Fig. 2. 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 solitons and repeats from round-trip to round-trip. Additional insight is obtained from the optical spectrum shown in Fig. 3. The spectrum exhibits a modulation which is characteristic of a constant phase relation between the solitons, thus suggesting that the trains of solitons contain bound states [19], or soliton crystals [20] depending on the number of solitons involved in a given sequence. The spectral period is 0.2 nm which corresponds to a temporal separation of 41 ps (such small delay cannot be directly measured with our oscilloscope whose resolution is about 75 ps). This value is confirmed by the autocorrelation trace given in Fig. 4. The latter shows that solitons are equidistant and, because there is no pedestal, they are not in relative motion. In addition the nearly triangular envelop is characteristic of a bound state (or a crystal). The initial soliton state is therefore a superposition of soliton crystals similar to those reported in [14]. Of course this could be confirmed with a reconstruction [30]. However we are not

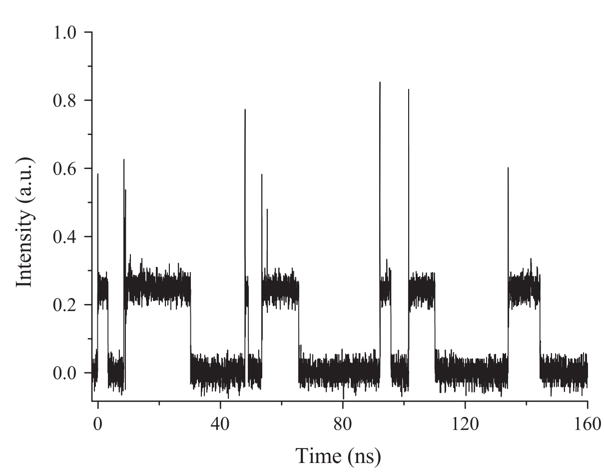

Fig. 2. Initial soliton distribution.