Intricate solitons state in passively mode-locked fiber lasers

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Abstract: We report a novel spontaneous soliton pattern formation in a figure-of-eight passively mode-locked erbium-doped double-clad fiber laser. It consists in a condensate phase in which there is almost periodic arrangement of alternate crystal and liquid soliton phases. Thanks to an adapted ansatz for the electric field, we perform a reconstruction allowing to clearly identify the soliton distribution along the cavity.

OCIS codes: (140.4050) Mode-locked lasers; (190.5530) Pulse propagation and temporal solitons; (140.3510) Lasers, fiber.

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1. Introduction

Passive mode-locked lasers are well known for ultrashort pulse generation. They have demonstrated their ability to generate several types of soliton complexes, especially in the anomalous dispersion regime. Ring cavities passively mode-locked through nonlinear polarization rotation (NLPR) [1–3] and figure-of-eight lasers (F8L) [4,5] constitute ideal tools for the investigation of nonlinear dynamics in dissipative systems [6,7]. Soliton pulse propagation has been widely studied in the framework of dissipative soliton dynamics [8–10].

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The scaling up of the output power of fiber lasers has allowed to considerably increase the number of coexisting solitons in passively mode-locked fiber lasers. Thus the number of interacting pulses has undergone a big step forward from a few tens to several hundreds, resulting in new and complex pattern formation dynamics. A “rain of solitons” dynamics has been reported in a NLPR laser configuration [11,12]. More recently, several ordered and disordered patterns presenting analogy with the states of matter were observed in ring cavities: soliton gas, soliton liquid, soliton polycrystal and soliton crystal [7]. It has been shown in [13] that these large solitons ensembles also appear in F8L thus demonstrating that they are universal properties of passively mode-locked fiber lasers operating in the anomalous dispersion regime. The characterization of these states becomes more complicated when some hundreds of soliton tend to group into a small part of the cavity. It is thus of importance to perform a reconstruction of the experimental results to clearly identify the temporal distribution of the solitons inside the cavity [14].

In this work we present experimental results of a new dynamics in an all-fiber F8L where a Nonlinear Amplifier Loop Mirror (NALM) is inserted in a laser ring to operate as a saturable absorber. An intricate soliton state, where several soliton packets in two different phases are simultaneously present inside the cavity, is observed. This particular state can be called a diphasic mixture of solitons by analogy with the terminology used in condensate matter physics.

2. Experimental setup

The experimental setup is schematically represented in Fig. 1. It is an all-fiber figure-of-eight laser based on a passive unidirectional ring (UR) cavity that is coupled to a NALM through a 50/50 fiber coupler. The NALM contains a double-clad Er:Yb-doped fiber amplifier manufactured by Keopsys, which consists of a 2.45-meter long double-clad fiber (DCF) that has a chromatic dispersion coefficient $\beta_2^{DCF} = -0.0247\ \mathrm{ps^2/m}$ at the operating wavelength $\lambda = 1.55\ \mu m$, and is pumped at 980 nm by a 4-W semiconductor laser. Two pieces of single-mode fiber (SMF 28, $\beta_2^{SMF} = -0.022\ \mathrm{ps^2/m}$) and dispersion shifted fiber (DSF, $\beta_2^{DSF} = 0.14\ \mathrm{ps^2/m}$) are used to control both the total cavity dispersion and the nonlinearity experienced by mode-locked pulses as they propagate. To favor multiple-pulse mode locking, the total dispersion is set in the anomalous regime with $\beta_2^{TOT} L \approx -0.04\ \mathrm{ps^2}$, with a total cavity length of 27.5 m corresponding to a round-trip time of 137.6 ns. The UR part is composed of an optical isolator and a 20%-output coupler. For high enough pump power and suitable length of the NALM, mode locking is obtained through the adjustment of the two polarization controllers (PC). 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).

3. Experimental observation

For a pump power of 3.2 W and an adequate adjustment of polarization controllers, we obtain the temporal distribution given in Fig. 2. The state consists of a set of confined pulses occupying a small part of the cavity. A more detailed inspection (zoom of Fig. 2) shows that there is an almost periodic series of peaks followed by plateaus. A peak with a width of 50 ps and a plateau with a width of 340 ps repeat several times to form a block of about 7 ns. The experiment shows that the solitons in the peaks are at rest while those of the plateaus are subject to fluctuations in amplitude suggesting that solitons move. Note that the increasing level of the plateaus is an artifact due to our photodetector.

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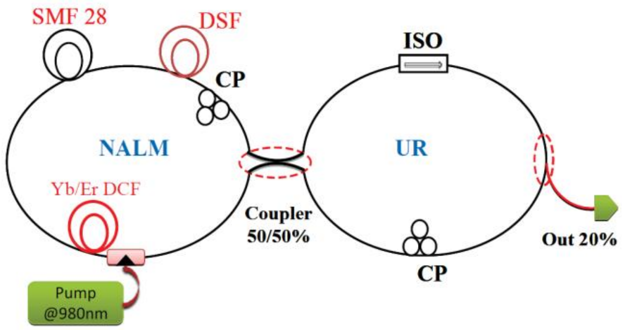

Fig. 1. Experimental setup. DCF: double-clad fiber; DSF: dispersion-shifted fiber; ISO: optical isolator; PC: polarization controller. NALM: nonlinear amplifying loop mirror, UR: unidirectional ring.

The peaks are therefore in a solid state while the plateaus are in liquid state. The autocorrelation trace of Fig. 3 suggests that, inside the peaks, the solitons could have some phase correlation and form a microcrystal. However no clear modulation is visible in the optical spectrum of Fig. 4. Indeed, the spectrum appears more noisy than modulated. The resolution of our oscilloscope was 50 ps and does not allow to determine the number of pulses within each state. However, from the autocorrelation trace, we can deduce the distance between pulses in the crystal phase, which is about 7 ps.

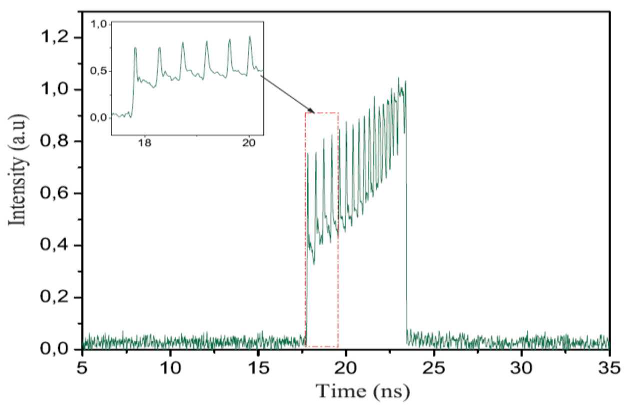

Fig. 2. Temporal trace of the soliton distribution (experiment).

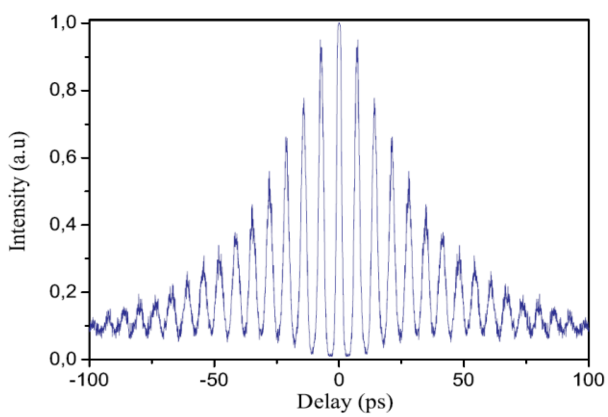

Fig. 3. Autocorrelation trace (experiment).

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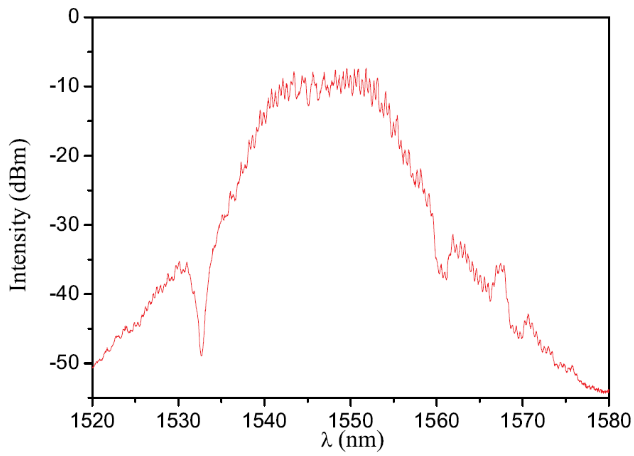

Fig. 4. Optical spectrum (experiment).

4. The reconstruction

To identify the distribution of solitons it is necessary to perform a reconstruction. For that, we consider an incoherent superposition of several packets of solitons, consisting in an alternate series of solid and liquid states.

In the case of solid state, the electric field for a packet of pulses is

$$E_n(t) = \sum_{\ell=1}^{\ell_n} A_0 \operatorname{sech}\left(\frac{t-\ell\Delta\tau_0}{\tau}\right) \exp i\left(-C\frac{(t-\ell\Delta\tau_0)^2}{2\tau^2} + \omega_0(t-\ell\Delta\tau_0)\right). \qquad (1)$$

In relation (1) all solitons are assumed to be the same, phase-locked and separated by a constant delay $\Delta\tau_0$.

In the case of liquid state, the electric field for a packet of pulses is

$$E_n(t) = \sum_{\ell=1}^{\ell_n} A_0 \operatorname{sech}\left(\frac{t-t_{\ell,n}}{\tau}\right) \exp i\left(-C\frac{(t-t_{\ell,n})^2}{2\tau^2} + \omega_0(t-t_{\ell,n}) + \Phi_{\ell,n}\right), \qquad (2)$$

with $t_{\ell,n} = \sum_{m=0}^{\ell} \Delta\tau_{m,n}$, $\Delta\tau_{m,n} = \Delta\tau_0 + \varepsilon_{m,n}$ and $|\varepsilon_{m,n}| << \Delta\tau_0$.

Here we assume that the position of a soliton in the liquid state is close to a fixed equilibrium value $\Delta\tau_0$, with a small jitter $\varepsilon_{m,n}$ varying randomly as $\Phi_{\ell,2p}$ does. The phases $\Phi_{\ell,2p}$ are distributed uniformly in [0,π] and $\varepsilon_{m,2p} = 1.9\cos w$ with *w* distributed uniformly in [0,π]. For the numerical computations we used a pulse length τ = 0.9 *ps*, a chirp parameter *C* = 0.3 and we take a separation $\Delta\tau_0 = 7\,ps$.

The total electric field consists in an incoherent superposition of alternate solid and liquid states:

$$E(t) = \sum_{n=1}^{N} E_n\left(t - \sum_{j=1}^{n} \Delta T_j\right), \qquad (3)$$

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where $E_n(t)$ is given by Eq. (1) for odd n and by Eq. (2) for even n, and ΔT_j is the separation between two successive states. On the basis of the experimental results we take $\Delta T_{2p} = \Delta T_2$ and $\Delta T_{2p+1} = \Delta T_1$ for every p.

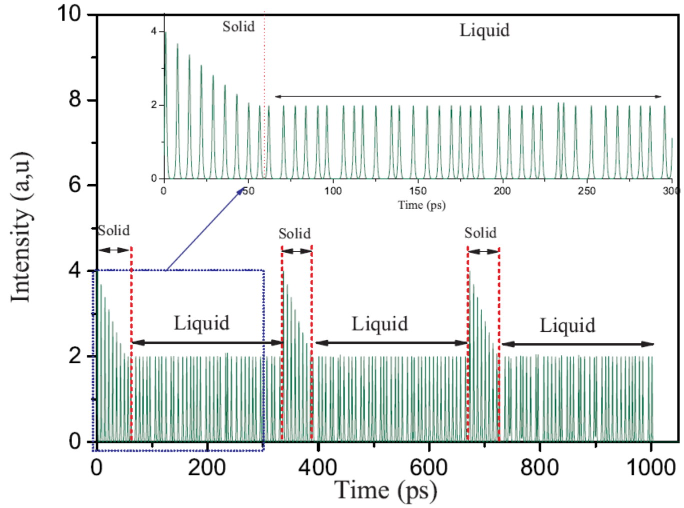

Fig. 5. Temporal distribution of a diphasic mixture of solitons (reconstructed).

First, we considered only a sequence of a single crystal and a single liquid to point out the influence of the coexistence of two phases on the autocorrelation trace. The pedestal at the edge and the return to zero in the center of the autocorrelation trace (not shown) characterize that the solitons forming the beginning of the distribution are at rest (crystal state) while the neighboring state includes moving solitons (liquid state). To get closer to the experimental data, the reconstruction of the autocorrelation trace was improved by considering a periodic succession of solid and liquid phases and a decrease of the amplitudes of the pulses in the crystal phase, as suggested by the temporal shape of Fig. 2. In order to reduce the calculation time we restricted to N = 6, with eight pulses in crystal states and forty in liquid ones. We checked that neither the reconstructed optical spectrum nor the autocorrelation trace is modified when increasing the number of pulses and/or the width of the temporal window. Hence, our choice is a good compromise between a reasonable calculation time and negligible consequences on the reconstructed data. The ansatz considered is shown in Fig. 5. In the liquid phase, all pulses are assumed to be identical and the amplitude of their relative movement increase with the distance from the crystal. The reconstructed autocorrelation trace is shown in Fig. 6(a) on a range large enough to reveal the entire structure. The most intense peaks in the center come from the autocorrelation of different crystalline states with itself. The secondary peaks located symmetrically result of correlation between different crystals. Figure 6(b) gives the details of the trace in the range experimentally achievable. One can note the very good agreement with the experimental results of Fig. 3, in particular with the return to zero at the center of the trace. The reconstructed optical spectrum with a triangular shape [15], shown in Fig. 7, seems to be modulated but closer inspection shows that no periodic structure appears but rather the spectrum is noisy because a large number of pulses were considered in the calculation.

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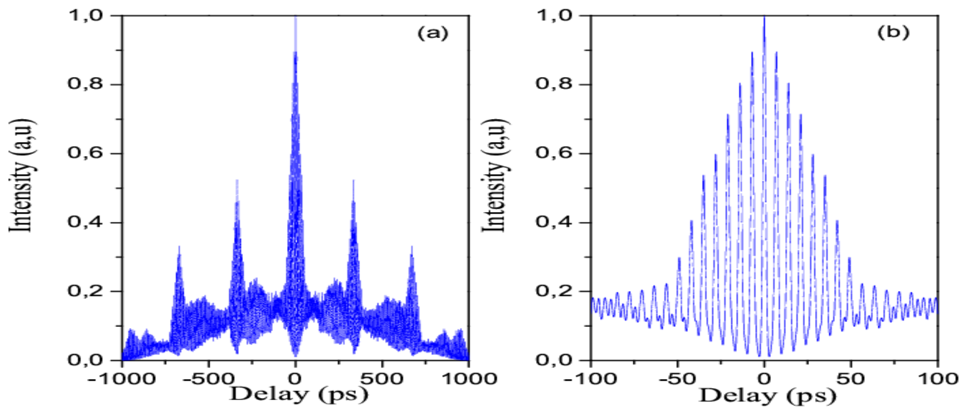

Fig. 6. Autocorrelation trace of a diphasic mixture of solitons(a), Zoom (b), (reconstructed).

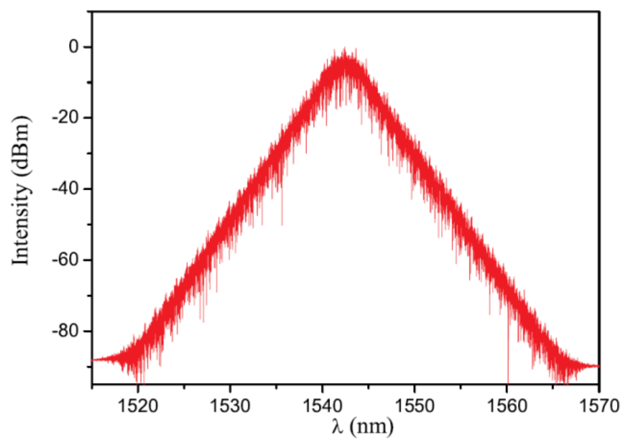

Fig. 7. Optical spectrum of a diphasic mixture of solitons (reconstructed).

7. Conclusion

In summary, we have reported an intricate soliton state in a figure-of-eight double-clad mode-locked fiber laser strongly pumped in such a way that a very large number of solitons interact in the cavity. More precisely it is a diphasic mixture of solitons containing a quasi-periodic series of alternate crystal and liquid soliton phases. We have conducted a reconstruction allowing to reproduce the experimental results. This reconstruction has permitted to see the influence of the presence of two phases on the autocorrelation trace and then to clearly characterize the distribution of the solitons along the cavity. Our results reported in the paper remain at a descriptive level. The understanding of the reasons for which different soliton patterns formation arise, will require the determination of a potential interaction between solitons. This task is actually under investigation.

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