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Invited Paper

Manipulating dissipative soliton ensembles in passively mode-locked fiber lasers

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ABSTRACT

We review our recent experimental and theoretical results addressing the dynamics of large numbers of solitons interacting in presence of a background in passively mode-locked erbium-doped fiber lasers. We first characterize experimentally the soliton rain complex dynamics, and then we focus on ordered soliton patterns. We report that, for suitable experimental parameters, a continuous wave can impose harmonic mode locking. Two levels of modeling for a mode-locked laser subjected to the external injection of a continuous wave are developed to support the latter observation. The first one is based on a scalar master equation, while the second one takes into account the mode-locking mechanism more accurately through a vectorial approach.

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1. Introduction

Although the area of passively mode-locked fiber lasers has witnessed more than 20 years of development, fiber laser dynamics remains under intensive investigations, since there remain many challenges at both fundamental and applied levels. Numerous applications require the increase of the pulse energy. For that purpose, it is necessary to limit the dynamics to single pulse operation. Significant increase of the pulse energy has been realized by using parabolic pulses [1,2] and, more recently, all-normal-dispersion cavities [3,4]. Another area of intense investigation is the realization of frequency combs [5,6], for which stable, multi-wavelength operation is needed in view of applications such as dense wavelength-division multiplexing [7] or optical metrology [8]. High-repetition-rate fiber lasers naturally deliver such frequency comb distributions [9]. However, the challenge is to obtain a flat spectral distribution with a tailored wavelength separation and enhanced comb stability [10]. In the temporal domain, these performances correspond to accurately controlling the pulse distribution along the cavity and, consequently, the interactions between ultra-short pulses. At the fundamental level, passively mode-locked fiber lasers constitute a one-dimensional-propagation nonlinear system in which dissipative solitons naturally manifest [11]. Fiber lasers constitute an ideal platform to investigate the interaction between ultra-short pulses, especially in the anomalous dispersion regime, where numerous solitons can be simultaneously excited at high pumping power [12–14]. Various soliton patterns, analogous to the states of matter, have been observed, regardless of the given mode-locking mechanism, highlighting universal interaction properties [15–20]. The soliton distribution in a cavity roundtrip is a direct consequence of these interactions, which can be either repulsive or attractive, depending on time scales and cavity parameters involved. Dominantly attractive interactions are responsible for the formation of bound states, which are composed of identical solitons [21], and whose size culminates in large soliton crystals [22]. Harmonic mode locking (HML) is the consequence of a dominantly repulsive interaction, which was until recently attributed to the gain relaxation dynamics [23]. However, in many HML fiber laser experiments, a continuous wave (cw) component has been noticed in the optical spectrum, suggesting that this component could play an important role in the HML mechanism [24–27]. In addition, it was theoretically shown that a small cw component allowed controlling the nature and the strength of the soliton interaction [28]. This prediction together with the observation of the cw component in the HML led several teams to investigate the influence of an external cw on the soliton distribution in passively mode-locked fiber lasers. The basic idea is to determine if it is possible to control the soliton interaction through continuous external injection. Let us note that continuous optical injection has

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been used to efficiently stabilize a passively mode-locked quantum dot semiconductor laser [29,30]. Indeed, these lasers usually suffer from waveform instability at high pump power. It was demonstrated that the external cw component had a stabilizing effect together with spectral narrowing.

The paper is organized as follows. To give the flavor of complexity that is associated with multi-soliton dynamics, we develop in Section 2 the study of the soliton rain dynamics. In the latter, soliton pulses are continuously generated from an extended noisy background and drift until they reach a condensed phase comprising several aggregated solitons. This quasi-stationary dynamics, which was observed in several cavity configurations [32–34], can be triggered with an external cw signal [32]. By using high-bandwidth detection electronics, we here highlight the interaction between the drifting solitons and the condensed soliton phase. Section 3 relates the experimental testing of cw injection to achieve high-harmonic mode locking, in a high-power double-clad Er-doped fiber laser. Starting from an irregular initial soliton distribution, we show that, under specific injection conditions, the external laser can force the mode-locked laser to operate in the HML regime [35]. Theoretical and numerical modeling approaches are considered in Section 4. The first approach is based on a universal master equation [36] in which a driven cw term is added. It shows that, starting from different soliton patterns, the external injected term induces a motion of the solitons then leading to various distributions [37]. The second modeling approach is based on a vectorial model, and considers the interaction of few solitons submitted to an external continuous field. It is demonstrated that under specific resonance conditions, repulsive or attractive interactions occur between solitons leading to harmonic mode locking or soliton crystal patterns, respectively [38].

2. Soliton rain

A common understanding is that mode locking appears as an abrupt transition between a noisy continuous wave regime and a “clean” short-pulse laser operation. However, complex short pulse dynamics, from stationary to pulsating and chaotic ones, have been found in the vicinity of conventional mode-locked regimes [39–42]. The concept of dissipative solitons provides a clearer understanding of the wide range of short pulse dynamics that can be accessed when the parameters of the laser system are varied [11]. In addition, mode locking has been identified to behave as a first-order phase transition, using statistical light mode dynamics [43]. These theoretical backgrounds help to understand the existence of partial mode locking, where mode-locked pulses coexist with a significant noisy or quasi-cw background. Soliton rain dynamics represents a stunning illustration of this situation, where soliton pulses and a noisy set of cw components, share the total cavity energy and interact in a dramatic quasi-stationary fashion [44].

This regime was found in a fiber ring laser cavity operated in the vicinity of conventional mode locking [32]. The laser cavity, sketched in Fig. 1(a), is built around a 2-m long erbium-doped fiber amplifier pumped by two 980-nm laser diodes with a maximal injected power of 800 mW. Mode locking is achieved by using nonlinear polarization evolution along the fibers, followed by intensity discrimination by a polarizer. Tuning the fibered intracavity polarization controllers shapes the nonlinear transfer function. With such flexibility, numerous dynamical regimes become accessible besides standard mode locking, by simply altering the orientation of the polarization controllers, among which the soliton rain dynamics described below.

Propagation in the anomalous dispersion regime combined with an intense pumping power ensures multiple-pulse operation with, typically, 10–100 soliton pulses, which tend to aggregate into a sub-nanosecond pulse bunch. At the same time, a significant fraction of the energy of the cavity remains in the quasi-cw background. This combination of mode locking and background components can be seen in the optical spectrum (Fig. 1(b)), with the presence of a quasi-cw spike in addition to the resonant radiation waves symmetrically located with respect to the center of the spectrum [45]. Such mixing of field components is also apparent in the temporal domain (see Fig. 1(c)), which reveals an inhomogeneous background. Importantly, the fraction of the weakly coherent background could be gradually varied by tuning the cavity parameters, similar to the alteration of the proportions of mixed phases in the course of a first-order phase transition.

Soliton rain is a complex self-organized dynamics, which takes place among large numbers of solitons and a substantial background. It is characterized by the interactions between three main field components. The first component is a bunch of several tens of bound and jittering solitons dubbed as the condensed soliton phase, since it appears analogous to a liquid thermodynamical phase [15,32]. This component appears as the main peak on oscilloscope traces, whenever the individual soliton constituents are not temporally resolved. Like a liquid would evaporate, the condensed phase emits a large amount of radiation on one temporal side. That radiation indeed moves to shorter times due to the conjunction of anomalous dispersion and spectral asymmetry of the radiated waves [44]. This temporal asymmetry can be seen on magnified oscilloscope traces, and is also consistent with the analysis developed in Section 4.2. This radiation also superimposes with other preexisting cw modes, altogether producing a noisy, inhomogeneous background with large fluctuations. When fluctuations exceed a certain level, a new soliton is formed, such as a droplet formed from a vapor cloud, which then drifts back to the condensed phase at a nearly constant relative velocity, as can be seen in the stroboscopic plots shown on Fig. 1(c and d). Note that the relative drifting of pulses is a continuous slow motion performed one cavity roundtrip after another, whereas stroboscopic plots display a discontinuous sequence of recordings where two consecutive traces are separated by a 40 ms lapse of time, which corresponds to around 6×10^5 cavity rountrips. This slow drifting motion of isolated pulses towards the condensed phase operates at a relative velocity of the order of 10 meters per second, and is thus observable in real time on the oscilloscope. The whole scenario repeats in a quasi-stationary fashion, in the reference frame of the condensed phase that circulates round the cavity.

Since there is a noise threshold above fluctuations can be amplified to form the drifting solitons, it is possible to set the cavity operation – by lowering the pumping power, typically – below that threshold, and trigger the soliton rain by the injection of an external laser. Such triggering was experimentally demonstrated in Ref. [32].

Despite operation in the anomalous dispersion regime provides the easiest access to multiple pulse formation required in the soliton rain dynamics, similar dynamics were observed with fiber ring lasers operated in the normal dispersion regime [33,46]. In addition, soliton rain has been reported in a figure-of-eight fiber laser [34]. These observations tend to indicate that soliton rain, despite its complexity, represents a universal class of laser cavity dynamics.

Because there is a conjunction of internal motion and long-term quasi-stationarity in soliton rain dynamics, it is interesting to investigate the exchange of energy between field components, keeping aware that the whole system is not conservative, but dissipative with a constant supply from the pumping source. The noisy cw background energy seeds newly formed solitons, and then these drifting solitons transfer energy to the condensed

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