Complex Self-organized Multi-pulse Dynamics in a Fiber Laser: The Rain of Solitons

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Abstract— We present experimental studies of new dynamics observed in a fiber laser operated in a highly-pumped but weakly mode-locked regime. In this situation, both soliton pulses and cw background coexist and interact. In a specific dynamics which we have called "soliton rain", additional solitons arise spontaneously in the cavity rom the fluctuations of a background and drift until they reach a condensed phase of aggregated solitons. This process can go on forever in a quasi-stationary fashion. We have characterized the "soliton rain" dynamics, explored neighboring dynamics, and demonstrated a convenient way to control the soliton rain threshold by injecting an external cw laser inside the fiber laser cavity.

1. INTRODUCTION

Passively mode-locked fiber lasers are ideal tools for the exploration of new areas of solitons nonlinear dynamics in an open, dissipative environment [1, 2]. A common understanding is that mode locking appears as an abrupt transition from a noisy cw operation to a clean — background-free — short-pulsed laser operation. However, there can be significant deviations to such scenario. The existence of dispersive waves that are radiated by the pulse as it travels through the discontinuities of the laser cavity medium can significantly alter the spectral and temporal pulsed features [3, 4]. For instance, the observation of noiselike pulses is an example of puzzling dynamics that does not fall in the conventional picture of mode-locked operation [5]. Such intriguing is the recent finding of the soliton rain dynamics, which corresponds to an intermediate regime where soliton pulses and cw components of comparable strengths not only coexist, but also interact in a dramatic way [6, 7].

2. OBSERVATION AND CHARACTERIZATION OF SOLITONS RAINS

Experiments are performed with a passively mode-locked fiber ring laser detailed in [6]. Passive mode locking (ML) is obtained through the ultrafast saturable absorber effect that results from nonlinear polarization evolution. The laser dynamics can be controlled through paddle orientations of polarization controllers (PC).

We have observed at large pumping power a gradual transition from the cw regime to the ML regime. This transition is described as follows. For a given initial orientation of the set of PCs, the laser operates in a noisy-highly multimode-cw regime. Change of the orientation of a PC produces first the appearance of weak ML components next to the cw components. As the PC is turned further the ML components become stronger, until the cw components disappear. In the intermediate regime, namely where the cw components and soliton pulses coexist in the cavity, *rains of solitons* are observed: new solitons arise spontaneously from fluctuations of the background and drift at constant velocity until they merge with a condensed phase of jittering bound solitons.

Soliton rain is due to the interaction between three elements — see Fig. 1: the noisy background, drifting solitons and the condensed phase. The noisy background is produced by a large number of quasi-cw components. In principle, these quasi-cw components can be produced out of: the amplified spontaneous emission (ASE), cavity cw modes and dispersive waves produced by solitons. On average, drifting solitons are created far apart each others (nanosecond separation) with respect to their temporal widths (around 1 ps). The probability of soliton creation depends on the background level which is not uniform. Once formed, one soliton drifts at a rather low constant speed of the order of 10 m/s. Eventually, it collides with the condensed soliton phase. The condensed phase comprises several tens of solitons in a bunch wherein there is a large timing jitter. Soliton rains detailed features -size of the condensed phase, number of drifting solitons and their drifting velocity can be adjusted along with cavity parameters [7].

In terms of global dynamics and energy flows we get a picture of the interactions between the three elements that make a soliton rain. The background, through the amplification of its fluctuations, seeds the creation of drifting solitons like a droplet would be formed from a vapor cloud. Then, drifting solitons feed the condensed soliton phase. Since the size of the condensed

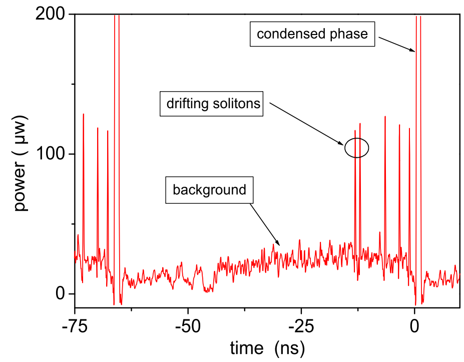


Figure 1: Output laser intensity — one cavity roundtrip time is 67 ns — showing the three field components of the soliton rain: the noisy background, drifting solitons and the condensed soliton phase.

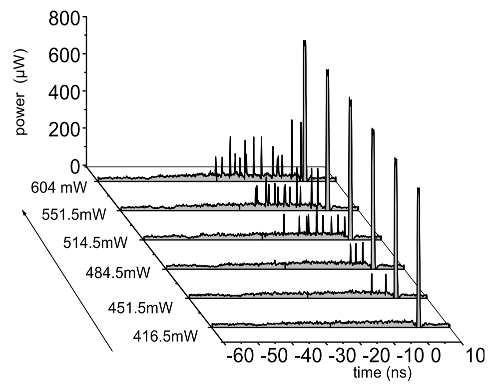


Figure 2: Influence of pumping power to soliton rain dynamics.

phase remains constant, this means that the arrival of new solitons causes the dissipation of a similar number of solitons. This dissipation releases additional radiation and dispersive waves that contribute to the background, such as the evaporation of liquid would contribute to the clouds. Because of these analogies with the cycle of water we have dubbed this fiber laser dynamics "rain of solitons".

3. CONTROL OF SOLITONS RAINS

Since the soliton rain starts above a certain level of background fluctuations, it is possible to control its appearance. One way of control is through the pumping power. The increase of the pumping power increases the level of fluctuations in the background. For a sufficient pumping power, the solitons rain starts with 1 or 2 drifting solitons at a time per cavity roundtrip, see Fig. 2. Increasing the pumping power further (450 mW–551 mW), the number of drifting solitons increases up to making up a heavy soliton rain (604 mW). At this point, the probability that two solitons are created closer together becomes significant, so that interactions between neighboring drifting solitons can manifest.

The second way in which we can increase the level of cw fluctuations, is via the injection of light into the cavity. We have demonstrated the control of the appearance and disappearance of the soliton rain by injecting an external cw laser, whose wavelength and intensity can be varied.

Here follows the experimental procedure: firstly, the pumping power is adjusted to be close below the soliton rain threshold, with the injected laser "off" see Figs. 3(a) and 3(b). After switching "on" the injected laser, the soliton rain starts and lasts as long as injection continues Fig. 3(c). When injection is turned off, the soliton rain stops almost immediately, after the last soliton created finishes its drift to the condensed phase. We note that the injected laser can trigger soliton rain only when its wavelength is on the short-wavelength side of the soliton spectrum. A small injected power level as low as 10 microwatts is sufficient to trigged the soliton rain Fig. 3(d). In addition to controlling the appearance and disappearance of soliton rain, it is possible to tune the soliton drifting speed, from 12 to 5 m/s when the injected power level increases from 100 to 220 microwatts.

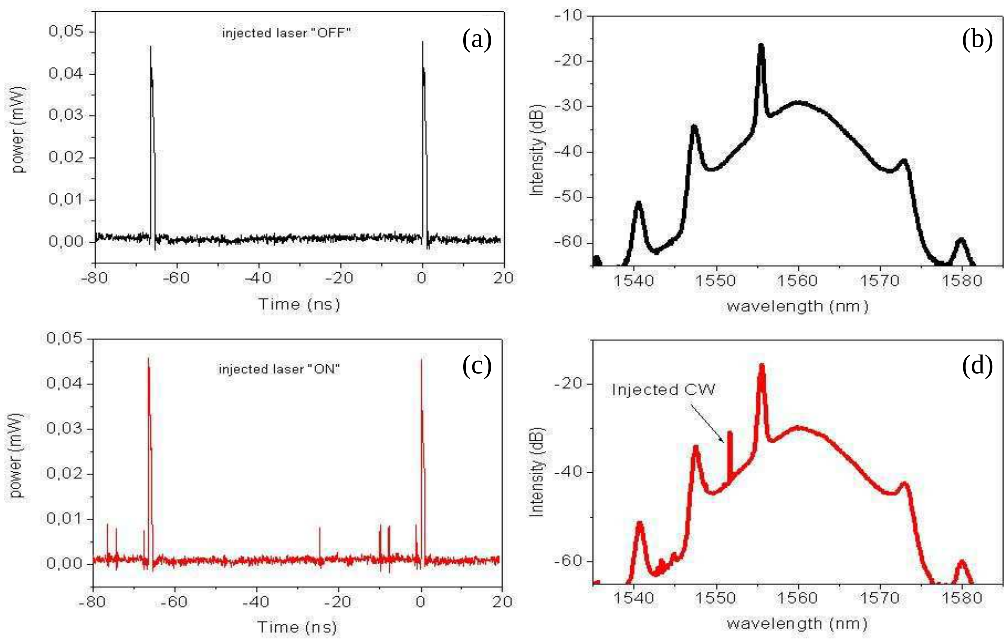
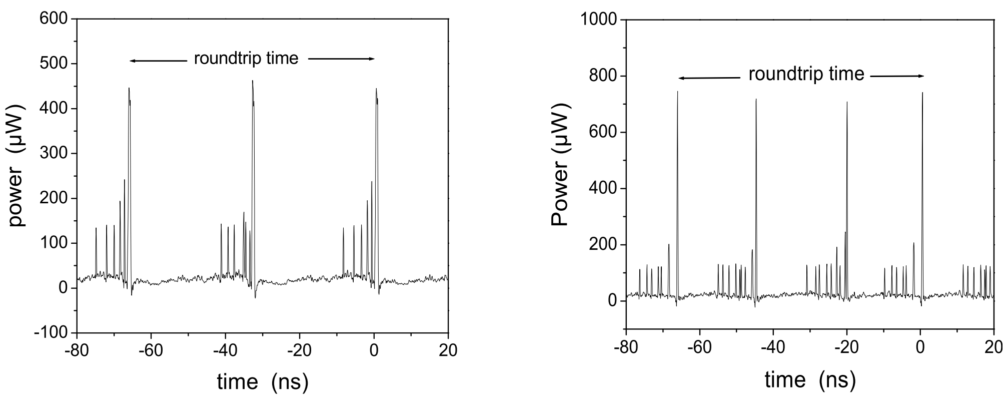


Figure 3: (a) Temporal optical intensity, injected laser off. (b) Optical spectrum, injected laser off. (c): Temporal optical intensity, injected laser on. (d) Optical spectrum, injected laser on.



(a) (b)

Figure 4: (a) Second cavity soliton rain harmonic at 30 MHz repetition rate. (b) Third cavity soliton rain harmonic at 45 MHz.

4. SOLITON RAIN HARMONICS

Close to the soliton rain, at high pumping power, we have observed soliton rain harmonics such as second (Fig. 4(a)) and third (Fig. 4(b)) soliton rain harmonics. The existence of soliton rain harmonics is due to the instability of the condensed phase when its size exceeds a certain level typically 40 solitons. The condensed phase then breaks into parts, and each new condensed part becomes related to its own background part that produces drifting solitons.

5. COMPARISON WITH OTHER SOLITON SELF-ORGANIZATIONS

5.1. Release of Solitons from the Condensed Phase

A typical soliton rain spectrum is presented in Fig. 5(a): it always features a cw peak on the short-wavelength side close to the center of the soliton spectrum, as well as stronger soliton sidebands on the short-wavelength side. However, we found specific settings of the PCs that produced an inversion with respect to the dominant spectral asymmetry. Both the cw and soliton sideband components now dominate on the long-wavelength side of the soliton spectrum — see Fig. 5(c). In the temporal domain, we observe the following: instead of drifting towards the condensed phase

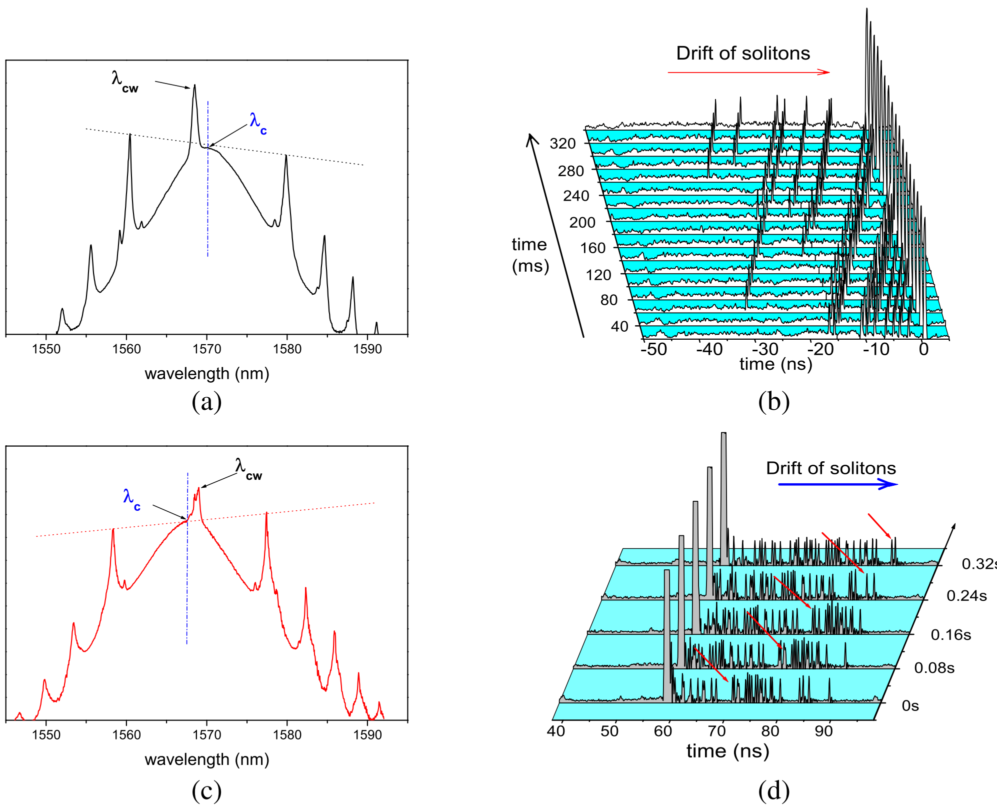


Figure 5: comparison between soliton rain dynamics where individual solitons flow towards the condensed phase and quasi-stationary release of solitons from the condensed phase: (a) optical spectrum of soliton rain, (b) corresponding stroboscopic recording of the temporal dynamics; and (c) optical spectrum of release of solitons, (d) corresponding stroboscopic recording of the temporal dynamics.

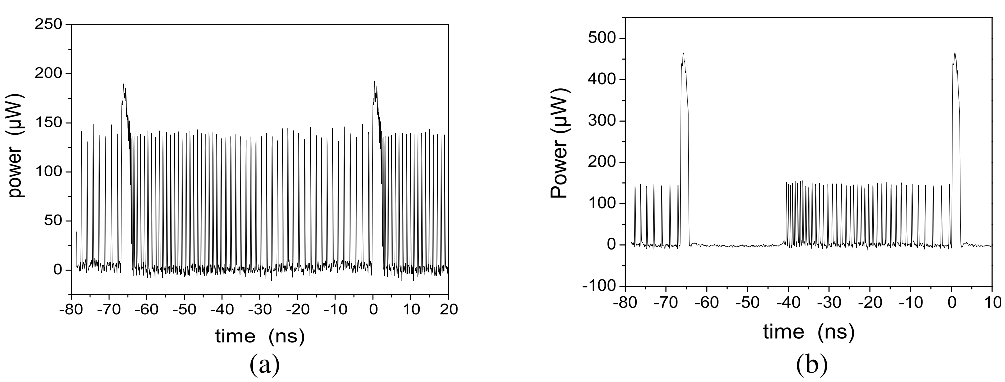


Figure 6: Chirped soliton trains and condensed phase: (a) chirped train filling the entire cavity; (b) chirped train partly filling the cavity and attached to a single condensed phase.

(Fig. 5(b)), the solitons are coming out of the condensed phase, flowing outward until they vanish inside the background (Fig. 5(d)). It becomes clear that the precise composition of the spectrum and the impact of chromatic dispersion dictate the temporal dynamics.

5.2. Coexistence of Stationary Chirped Trains and the Condensed Phase

Close to the domain of existence of soliton rains, we observed other examples of self-organization of dissipative solitons, where the drifting motion is absent and the observed patterns appear stationary.

One example is the *chirped trains and condensed phase* pattern: in this dynamics the individual solitons are stationary, they get organized with their neighbors in a train of pulses whose separation increases with time. In Fig. 6(a), the chirped train fills the entire cavity and is attached to the condensed phase at both ends. In Fig. 6(b), the chirped train occupies two-thirds of one cavity round trip and is attached at one end of the condensed phase. The extension of the chirped train can be almost continually selected by a fine tuning of the orientation of PC. We assume that the non-uniformity of soliton-soliton spacing is caused by the non-uniformity of the background [6]. Tuning the PC is indeed able to translate or alter the effective non-linear transfer function so as to increase or decrease the level of background and radiation that live in the cavity along with solitons.

6. CONCLUSION

Soliton rain is a complex but beautiful illustration of self-organization among large number of solitons and radiation components. It is observed in a fiber laser operated at anomalous chromatic dispersion, high pumping power, and weakly mode-locked regime. The dynamics is due to interactions between three field components: from **background fluctuations**, additional **drifting solitons** are created and drift at constant relative velocity until they merge with a bunch of several tens of bound jittering solitons which we called the **condensed phase**. Since the size of condensed phase remains constant, the condensed phase emits a large amount of radiation that contribute to the background. The whole scenario repeats in a quasi-stationary fashion. Building a comprehensive theoretical model able to retrieve such complex interactions among large number of cw and solitons components is a challenging task that needs to be undertaken.

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