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Invited Paper

Multisoliton complexes in fiber lasers

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ABSTRACT

The formation of stationary and non-stationary pulse groups is regularly observed in multiple pulse soliton fiber lasers. The environment developed in this study for the flexible investigation of this phenomenon is based on the cavity comprising a semiconductor saturable absorber mirror (SESAM) with complex dynamics of absorption recovery and all-fiber dispersion management. The detailed experimental and theoretical considerations show that multiple pulsing in fiber systems offers numerous embodiments ranging from stationary bound states to chaotic bunches. The pulse interaction through the dispersive waves was found to produce a principal impact on the bound state formation. The stability and transformation of stationary bound states and bunch propagation have been also addressed.

1. Introduction

The multiple pulse regime is a general attribute of mode-locked lasers exploiting soliton propagation. Various multisoliton ensembles can be developed by balancing nonlinearity and dispersion in the presence of energy exchange within a cavity environment. The self-organization dynamics of localized objects, known as dissipative solitons [1,2], arise due to the energy redistribution between constituents of the soliton complexes [2–7]. A strategy based on dissipative effects could lead to the formation of dissipative solitons and multisoliton complexes and would allow their potential as sources of ultrashort pulses with large energy scaling to be exploited. The aim of this study is to investigate the role of the energy dissipation mechanism in the soliton interactions and in the formation of pulse groups having different forms and characteristics, e.g. bound states, bunches and rains. The correct analysis of different soliton oscillators requires an adequate model to be developed, which takes into account pulse propagation in a cavity where the nonlinear response and energy dissipation are provided by saturable absorption and a gain medium.

Dissipative solitons are defined as weakly interacting solitary objects with random phase distribution [1,8]. The energy exchange between pulses can lead to the formation of identical solitons and soliton complexes which circulate in the cavity as a unified entity. The formation of three types of soliton complexes in laser cavities has been reported to date. The first type is stationary solitons tightly pulled together, and is called bound solitons, or soliton molecules [9]. Two others types, known as bunches of solitons [10,11] and soliton rain [12–15,16], are non-stationary complexes exhibiting continuous soliton motion within the group.

Bound solitons or soliton molecules are stable and tight packets of solitons, characterized by a fixed, discrete pulse separation independent of propagation [3,17–24]. In terms of pulse separation, bound solitons can be divided into two categories: tightly or loosely bound solitons [23]. Tightly bound solitons have short pulse interval of less than a few pulse widths, and are formed through the direct soliton interaction [25]. In contrast, loosely bound solitons interact with each other through dissipative effects such as saturable absorption, spectral filtering and competition in a slowly saturating gain medium, while the overall impact of the direct soliton interaction is negligible [10,11,25]. The continuous energy exchange/flow in the cavity due to dissipative effects can cause pulse interaction at a long distance, and eventually result in the formation of stationary states of identical solitons circulating as unified objects with specific phase trajectories.

A bunch of solitons is a packet of tightly bound solitons oscillating continuously [10,11]. This type of soliton group was originally observed in a fiber laser mode-locked by a semiconductor saturable absorber mirror (SESAM) with a bi-exponential response [10,11]. The fast component of the SESAM is responsible for the start-up of the soliton regime, while the slow component provides the trapping of pulses resulting in the formation of a tightly packed soliton group formation. When the temporal length of the group is less than the decay time of the absorber, the joint action of the pulses forming the group provides more complete saturation of the absorption, and thus the pulses suffer lower losses compared to the regime with the absorber saturated by individual pulses.

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The direct soliton interaction prevents the collapse of the bunch, and in conjunction with an attractive force originating from the slow recovery component of the SESAM, results in the continuous motion of pulses within the group. The complex soliton dynamics within the bunch are related not only to direct interpulse interactions, but also to the influence of intense dispersive waves on the pulse envelope and phase. Arbitrary phase changes randomize the direct soliton–soliton interaction and contribute additional chaos to the dynamics of the solitons inside the bunch. This is manifested in fluctuations of the average interpulse distance, a phenomenon known as bunch breathing.

Soliton rains are clusters of solitons containing three components: the condensed soliton phase, which is a bunch of several tens of bound jittering solitons, a group of drifting solitons, and a noisy cw background [12–15]. The soliton rains exhibit chirped allocation of the pulses and which is related to three mechanisms producing a repulsive force pushing the solitons away from each other: gain relaxation dynamics (gain depletion), interaction of solitons with a dispersive wave, and the electrostriction effect [12,13]. The dominance of one or other mechanism, which is dependent on laser configuration, determines the structure and dynamics of the soliton complexes.

In this article we analyze the role of laser parameters in soliton dynamics and the formation of stationary (bound solitons) and non-stationary (bunch of solitons) groups. We consider both experimental and simulation results which shed light on the nature of soliton interactions. Although a number of parameters affect soliton group formation simultaneously, we distinguish in particular the impact of the saturable absorber, dispersion management, and nonlinearity. The article is built as follows: Section 2 classifies the soliton complexes in terms of the strength of the dissipative effects. Section 3 is devoted to a description of the numerical simulation; the main equations and parameters are defined. Section 4 describes experimental and theoretical investigations into the influence of a bi-exponential SESAM on the formation of bunches of solitons. Sections 5 and 6 describe observations of the role of dispersion management, including total cavity dispersion and dispersion of the active medium, in soliton interaction. The impact of nonlinearity is considered in Section 7. Conclusions and remarks concerning this work are summarized at the end of the article.

2. Classification of soliton complexes

The soliton groups considered in this article will be classified within the context of the theory of dissipative soliton systems. Dissipative soliton formation requires an appropriate loss-gain balance, in addition to the balance between dispersion and nonlinearity sufficient for classical, "conservative" solitons in Hamiltonian systems. The dissipative mechanism can be distributed or lumped. For theoretical consideration the action of dissipative lumped elements is averaged. As a result we get a distributed model described by the Ginzburg–Landau equation [1,8,26]:

$$i\frac{\partial\psi}{\partial z}-\frac{\beta_2}{2}\frac{\partial^2\psi}{\partial\tau^2}+\gamma|\psi|^2\psi=iG(z,|\psi|^2,\ldots)\psi. \qquad (1)$$

The equation involves the following variables and parameters: $\psi(z,\tau)$ – slowly varying amplitude of the field, z – the propagation distance, τ – time in the associated coordinates, β_2, γ – values of the group velocity dispersion (GVD) and the coefficients of the Kerr nonlinearity. The right side of the equation describing all dissipative forces of the system is. Generally, Eq. (1) is regarded as the principal equation for description of the complex dynamics of dissipative solitons in complicated systems with multipulse background radiation. Dissipative effects in a system are described by the function $G(z,|\psi|^2,\ldots)$, taking into account numerous factors including saturated linear and nonlinear gain, saturable absorption, spectral filtering, the active modulators, etc. [1,2,8]. We should note, that "the range of action" of the acting dissipative forces may be "local or short" or "global" for example covering the whole laser cavity [27].

Let's consider the basics of the dissipative solitons dynamics and define a classification of dissipative group states by specifying a set of laser system parameters, which determine the dissipative properties of the system. If it is possible to average the rapid changes of the pulse envelope, a promising approach for the consideration of their dynamics can be an averaged equation of the «guiding center» type [28,29]

$$i\frac{\partial\psi}{\partial z}+\frac{D}{2}\frac{\partial^2\psi}{\partial\tau^2}+|\psi|^2\psi=R(\psi,\psi^*),\quad |R|\ll 1, \qquad (2)$$

with averaging over a propagation period much less than the full optical path-of the cavity round trip time, for example. Dissipative effects in the system, as well as interaction with other pulses, are considered as an adiabatic perturbation $R(\psi,\psi^*)$ of the fundamental soliton dynamics of the NSE. The equation is written in a soliton system of units, however, considering "soliton" lasers, we restrict ourselves to the case of anomalous dispersion, $D = 1$. In this approach the form of the soliton envelope is preserved and perturbation effects are associated with adiabatic changes of its parameters – amplitude, duration, frequency. Small values of $|R|\ll 1$ correspond to limited dissipative effects and weak dispersive waves, which appear in the spectrum as relatively narrow «sidebands» [30,31]. In this approximation, we can consider complex and multi-pulse dynamics, which after the establishment of steady state equilibrium are characterized by an arrangement of pulses associated with a balance of "transverse" forces J acting on each pulse [28]:

$$J[\psi]=\mathrm{Im}\int_{-\infty}^{\infty}(R\psi_\tau^*-R^*\psi_\tau)\mathrm{d}\tau=0. \qquad (3)$$

In this case, the characteristic feature of the pulse state is small-amplitude perturbation trajectories (low jitter), for example, harmonic mode-locked solitons. In the presence of binding between the pulses, this type of soliton forms coherent bound states with equidistant pulse separation. Their spectrum has a specific modulated structure, which manifests a constant phase difference between the pulses [17–24].

Growth of perturbation, R, in absolute value corresponds to growth as the gain, as losses, and stronger nonlinear transformations. A typical scenario in this case is the acceleration of energy exchange between the spectral components, the generation of a wide range of dispersive waves, an increase in the number of pulses in the cavity, and a reduction of the distance between them. The presence of a strong background of chaotic dispersion waves violates the assumption of an averaging of the pulse characteristics, moreover, the form of the pulse envelope is essentially different from the fundamental sech^2 – pulse of the NSE. In the spectrum it is expressed as modification into a "triangular" shape, an increasing of intensity, and a broadening of «sidebands» [11,32,33]. Changes in the complex dynamics are related to both the influence of a random field of dispersive waves and a decrease in the average distance between pulses (the latter may be caused as a result of strengthening of interactions and the formation of a greater number of pulses). Obviously, in this case the coherence of bound states is violated, however, if the relationship between the pulses, provided by dissipative mechanisms (e.g. a saturable absorber), is strong enough and exceeds interpulse repulsion, then the state is not destroyed and becomes a chaotic bunch of solitons [3,10,11,34].

A set of solitons in a fiber laser resonator can be part of more complex and integrated dynamics [27,35,36]. A bright example of

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