Soliton Pair Dynamical Transition in Mode-locked Lasers
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Abstract: We report a dynamical transition between steady states of optical solitons in a mode-locked fiber laser. We model the transition theoretically using a Haus equation-based numerical simulation and a simplified analytical model. © 2023 The Author(s)

1. Introduction
Dissipative solitons are localized waves in open systems far from equilibrium, whose existence results from a balance of dissipative, dispersive and nonlinear effects. The self-assembly of solitons into nonlinear superpositions of multiple solitons plays a key role in the complex dynamics of mode-locked lasers [1]. These states are extensively studied in light of their potential technological applications and their resemblance to molecules [2]. However, progress along these endeavors is still held back by the lack of effective means to manipulate multi-soliton waveforms.

Here, we show it is possible to control soliton interactions in a mode-locked fiber laser, using a single control knob, the laser gain [3]. We experimentally demonstrate a two-orders-of-magnitude reduction in the separation of bound soliton pairs by sweeping the pumping current of the laser. The sweep induces a dynamical transition between a phase-incoherent loosely bound state, and a phase-locked tightly bound state.

2. Experimental Observation
Our experimental protocol starts by generating stationary states of soliton pairs by increasing the pumping current to 124 mA, beyond the threshold for stable single-pulse operation (inner arc of Figure 1a), creating a pair of solitons (central and outer arcs). At high gain values, the solitons are loosely bound (outer arc) by the noise-mediated interaction (NMI) [4,5], which is heavily influenced by the exponentially decaying pedestals that often appear around soliton waveforms in mode-locked lasers [4,6]. After achieving a loosely bound steady state, we lower the pumping current and observe a reduction of the solitons’ separation time as a result of the reduction of the pedestals energy until eventually, the solitons snap together and coherently lock at a separation comparable to their width (central arc).

The laser setup is an all-fiber integrated ring cavity operated in the anomalous dispersion regime and is presented in Figure 1(b) [7]. An erbium-doped fiber is core pumped by a 976nm diode laser through a wavelength-division multiplexer. A polarization-independent optical isolator ensures unidirectional lasing, two fiber polarization controllers tune the overall low cavity birefringence, and a 90/10 coupler provides the laser output. The mode-locking operation is passively achieved by employing a nonlinear multimode interference-based saturable absorber. The laser output is analyzed with an optical spectrum analyzer, and a fast photodiode connected to a real-time oscilloscope.

We start by studying the time-domain traces of the output intensity (Figure 1(c)), exhibiting two peaks that approach each other as the pumping current is decreased. For pumping currents below 121 mA the soliton separation is too small to be resolved in Figure 1(c), yet the approximate conservation of total energy in the soliton waveform indicates that the number of solitons has not changed. We continue by studying the output spectrum as a function of the pumping current (Figure 1(d)). At pumping currents above 120 mA we do not observe spectral interference fringes, indicating that the solitons are not phase-locked, and they form a loosely bound state. At pumping currents below 120 mA, we observe an abrupt appearance of spectral

Figure 1. Soliton dynamical transition in a mode-locked fiber laser (a) The laser gain is used as a knob to control a dynamical transition between loosely and tightly bound soliton pairs. (b) Experimental setup. SA: saturable absorber, SMF: single-mode fiber, MMF: multimode fiber, EDF: erbium-doped fiber, WDM: wavelength-division multiplexer, ISO: optical isolator, PC: polarization controller, OSA: optical spectrum analyzer, OSC: oscilloscope. (c) Oscilloscope trace versus pumping current. (d) Optical spectrum analyzer trace versus pumping current.
fringes, indicating that the solitons interact coherently so that their phases lock, i.e. the solitons have transitioned into the tightly bound state.

3. Numerical simulation and simplified analytical model

The temporal dynamics of dissipative solitons in fiber lasers are conveniently modeled by the Haus master equation for mode-locked lasers [8]. To model the dynamical transition, we derived a generalized master equation that includes all the physical processes needed to observe both the long- and short-range interactions. We numerically integrate the equation to simulate the soliton pair dynamical transition.

To observe the transition, we apply the following protocol. First, we initiate the simulated cavity with two solitons. Next, we propagate the input field many cavity lengths, and then abruptly decrease the unsaturated gain. The simulation time domain and spectral results are presented in Figure 2(a) and (b) respectively. The time domain plot shows two solitons in a loosely bound state for the initial third of the propagation. Then, the unsaturated gain is abruptly reduced (white dashed line in Figure 2(a,b)), causing the energy of the pedestals to drop, and the solitons to drift towards each other until finally, a tightly bound steady state is reached, as indicated by the stable spectral fringes in Figure 2(b).

To further emphasize the role of NMI, we model the interaction using a model first proposed in ref [4]. We find a threshold of pedestal energy under which no loosely bound steady state exists. The realm of the steady state diagram under this threshold (black portion of Figure 2(c)) represents the tightly bound state.

As the pumping current is lowered, therefore, two scenarios may occur. The first scenario is that the separation time decreases until the coherent interaction takes over at short separations. In this scenario, a dynamical transition occurs, after which the separation between the pulses, together with their relative phase, are locked by the coherent overlap interaction. In the second scenario, when the pumping current is lowered, the soliton-pair state becomes unstable to pulse annihilation before the threshold for the transition between the loosely and tightly bound states is reached.

Figure 2. Soliton dynamical transition in a numerical simulation and analytical model. (a) The simulated laser temporal intensity waveform as a function of propagation distance. The two solitons begin in a loosely bound steady state. Then, as the pumping current is abruptly lowered, the solitons drift towards each other until reaching a tightly bound steady state, as indicated by the spectral fringes in (b). (c) The calculated separation time as a function of the pedestal energy and width. The area marked in black indicates that the pedestal energy is under the critical value for a loosely bound steady state, and thus, the solitons are tightly bound.

The dynamical transition, along with the new understanding presented here of the interplay between the long- and short-range interactions will allow novel ways to control multipulse bunches, providing a significant step toward the goal of multipulse waveform engineering.

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