2015 European Conference on Lasers and Electro-Optics, (Optical Society of America, 2015)
Paper EF-5.4

Dark Soliton Statistics during Radiation Build-Up of Bright Dissipative Solitons in Long-Cavity Mode-Locked Fiber Lasers

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Long-cavity, all-normal dispersion mode-locked fiber lasers (LFLs) have recently attracted considerable interest, both as high-energy pulse sources and for their rich intra-cavity nonlinear dynamics. Such lasers typically support stationary states in the form of highly-chirped broad pulses, which are examples of dissipative solitons found in a wide range of physical systems [1,2], thus offering a convenient platform for studying nonlinear wave interactions.

By numerically simulating a LFL, we recently revealed quasi-stationary dark soliton structures in the radiation build-up dynamics from noise to a stationary bright pulse [3]. Here, we study for the first-time the long-range order and interaction of these dark features (in a simulated 120 m Yb:fiber system), which co-exist with stochastic radiation throughout laser turn-on. Fig. 1a shows an example of the spatiotemporal evolution. We employ a tracking algorithm to identify and record the trajectories (Fig. 1a inset) of dark features commensurate with dark solitons: a zero-dip and π phase jump (Fig. 1b) [4]. Many structures satisfy this condition for a number of iterations of the cavity, defined as the effective lifetime. For dark solitons in the wings of the evolving bright pulse, the background gradient imparts velocity on them [4], resulting in a curved trajectory since they travel at a different group velocity to the background bright pulse and rapidly decay. Remarkably, dark soliton structures can also emerge sufficiently close to the peak of the bright-pulse that they experience a near uniform background, and persist for many hundreds of round trip, suggesting quasi-stationarity. We note that collisions between solitons (of varying blackness) can perturb (Fig. 1c) or fully destabilize dark structures, leading to their rapid decay.

The evolution and dark soliton trajectories differ each time the simulation runs, since the model is seeded by stochastic noise, but simulations always converge to form the same steady-state bright pulse. To understand the probability of persistent dark solitons during radiation build-up, we process an ensemble of 100 simulations to compute a histogram of dark soliton lifetimes (Fig. 1d), neglecting structures with lifetimes shorter than 3 cavity iterations. A long-tailed, highly-skewed distribution is observed, indicating that long-lived dark solitons, although statistically less likely, do occur with a non-negligible probability. In such cases, the number of cavity iterations, and therefore the time, before reaching a steady-state is increased, which has implications for defining the laser start-up time in applications requiring a steady train of stable pulses.

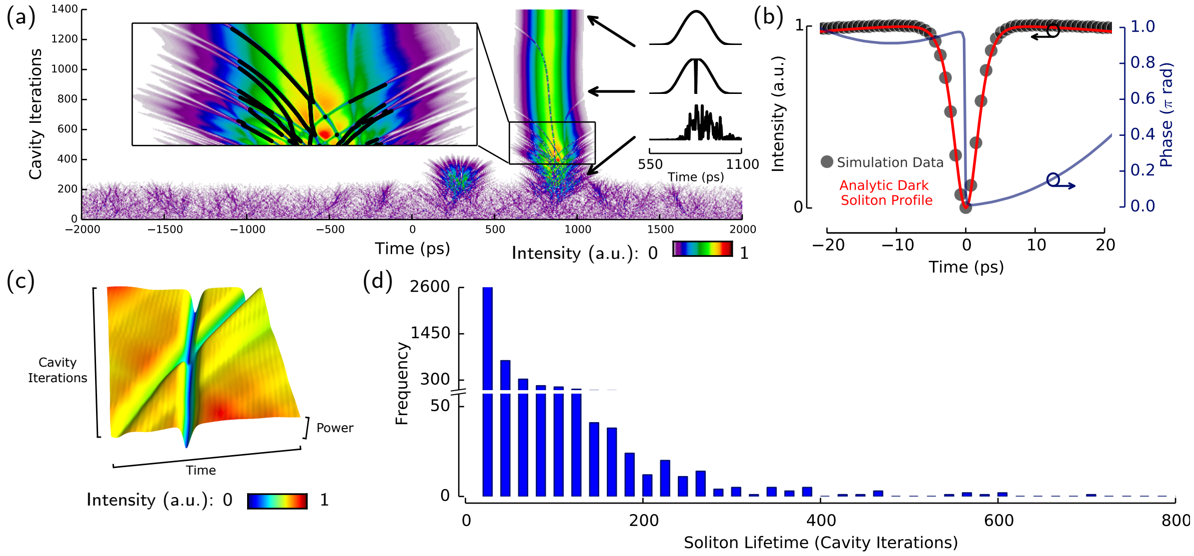

Fig. 1 (a) Spatiotemporal evolution throughout radiation build-up (inset: tracked dark solitons, highlighted in black). (b) Temporal profile and phase at peak of 800th iteration. (c) Black-gray soliton collision. (d) Histogram of dark soliton lifetimes.

In conclusion, our results shed new light on the nonlinear interactions in the starting evolution of mode-locked lasers, paving the way to a deeper understanding of such complex regimes which could improve long-cavity laser performance. Further work is underway to consider techniques to influence dark soliton dynamics.

References

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978-1-4673-7475-0/15/$31.00 ©2015 IEEE