Dissecting the Mechanisms of Spatiotemporal Mode-Locking

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Abstract: We uncover the mechanisms behind a range of new 3D solitons in multimode lasers using an approach called attractor dissection. Experimental measurements allow us to decompose multimode states containing up to 30 million locked modes. © 2020 The Author(s)

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Mode-locked light sources extend frontiers of knowledge. Today, their unique qualities, unmatched temporal and frequency precision, and peak energy density, make them essential for techniques spanning biology, chemistry and physics, and have led to at least three Nobel prizes. While light sources involving the self-organized synchronization of (one-dimensional) longitudinal modes within lasers and coherently-driven passive resonators have been systematically studied for decades, higher-dimensional mode-locking remains mostly mysterious [1]. As mode-locked lasers and microresonator frequency combs today are becoming commercial instruments, scientists may now look to higher-dimensions, which represent arguably the greatest unknown frontier in mode-locking science. With each new breakthrough in mode-locking science has come seemingly dozens of breakthroughs through applications. If the complex physics of high-dimensional mode-locking can be likewise understood, controlled and harnessed, then perhaps we can anticipate a similar pay-off in a next generation of novel, enabling light-based scientific tools.

Spatiotemporal mode-locking (STML) is 3D mode-locking in nonlinear optical resonators [2-3]. In 2017, Wright et al. observed STML in multimode fiber lasers by making use of low modal dispersion, graded-index fibers [2]. However, this work unveiled only some basic, overarching mechanisms behind some particular examples of STML phenomena.

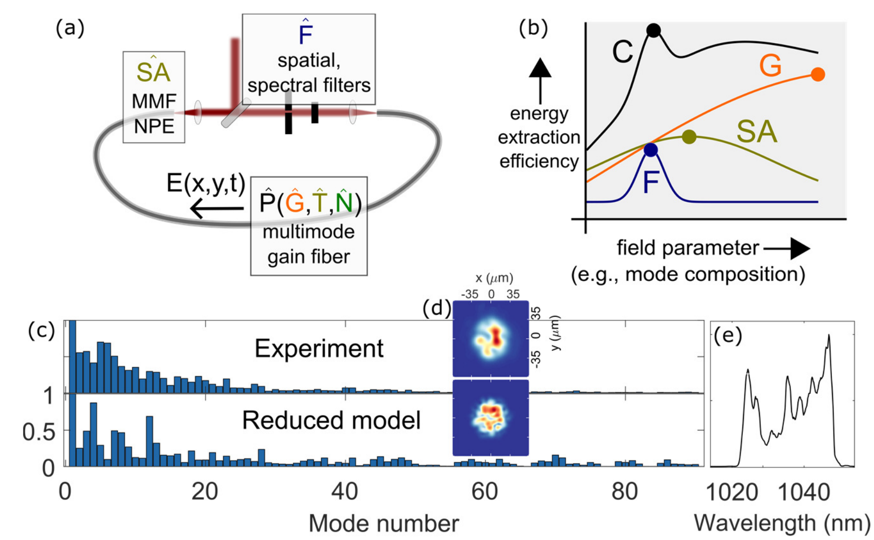

Fig. 1: Understanding STML through attractor dissection theory [3]. (a) shows a schematic of the experiment and full numerical model. (b) shows the approximate intuition for the laser steady state as a factorizable optimization problem: the laser "tries" to extract the most energy from the gain medium. (c-e) show the experimental and numerically-obtained distribution of transverse modes, the beam profiles (d) and the experimental spectrum, for a complex 3D mode-locked state.

Here we make use of a new theoretical approach called attractor dissection to break down complex 3D laser physics into simple, mechanistic models, allowing us to explain a variety of new kinds of 3D mode-locking observed in a multimode fiber laser [3]. These theoretical predictions are supported by numerical simulations, and by experiments in which we resolve the up to 30-million locked 3D modes that can be involved in experimental

STML states. Figure 1 presents a sample of our method and examples of some results. A 3D mode-locked laser can be thought of as a nonlinear, iterative map acting periodically on the intracavity field (Fig. 1a). In attractor dissection, we examine scenarios in which certain contributing components in the total model can be neglected, a process which is intuitively (though only approximately) analogous to considering distinct objectives within a factorizable multi-objective optimization (Fig. 1b). Briefly, as the parameters of a 3D laser are manipulated, one is manipulating which combinations of modes will most efficiently extract energy from the gain medium. In general, the steady-state observed in the 3D laser is the one that best realizes this energy extraction. This can be seen as a generalization of the well-known 'minimum loss' intuition of 1D mode-locking: it is, in effect, laser Darwinism [4].

Figure 1c-e show an example of a complex 3D mode-locked state, observed under similar conditions in a reduced model (derived via the attractor dissection approach) and in an experimental multimode fiber laser. While agreement is mainly qualitative, the model is able to capture the core distinguishing features of the mode-locked state, such as how many transverse modes are involved, resulting in a complex and broadly-spread multimode beam. Despite this, the pulse that forms is short (~1 ps in duration, and chirped) but complex, with excellent RF spectral contrast (>100 dB), indicating that, despite apparently significant short-range disorder, the laser has developed highly-stable long-range order. By assessing the simplified model that best describes this situation, we determine that this kind of pulse is formed due to the laser's joint optimization of a minimal loss through the intracavity saturable absorber, and the maximum overlap with the broad gain medium of the multimode fiber.

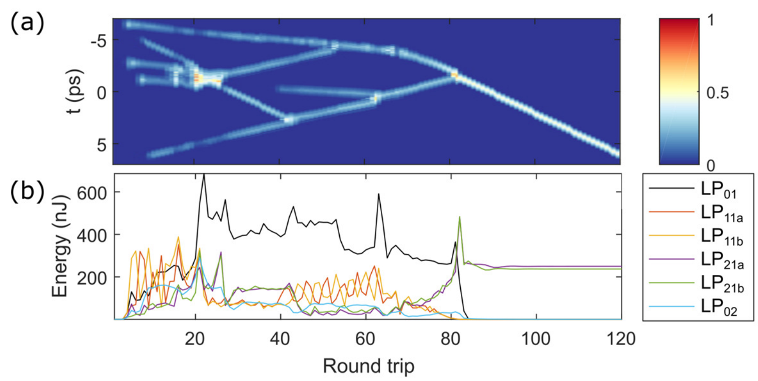

Fig. 2: Competition among 3D dissipative solitons (simulations). In a 3D laser, many similarly-optimal solutions to the energy extraction problem may exist, and consequently it is common to observe competition between multiple pulses. Unlike in most single-transverse-mode systems, in 3D these pulses travel at different velocities, and therefore collide – and annihilate – leading to a single winning pulse. (a) shows the intensity of the field in the laser over time and subsequent round trips, while (b) shows the energy distribution among different transverse modes. The winner of the competition in this case is an effectively single-mode pulse, similar to those recently observed in [5].

Of course, this work is only a step towards understanding (never mind controlling or exploiting) 3D mode-locking. While attractor dissection can help explain steady-state regimes of STML, 3D mode-locking physics is full of new, non-steady-state phenomena as well. Figure 2 presents a numerical example: spatiotemporal competition among 3D dissipative solitons. To understand processes like this, and/or the complex mixture of disorder and order in Fig. 1c-e, we need not only novel optical measurement tools, but also new theoretical tools, ones which may permit a general understanding of mode-locking physics [6-7]. To control these processes – and reap the benefits of novel capabilities for mode-locked light sources – we will likewise need further innovations in control of complex light (e.g., [8]).

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