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# Smart fiber lasers encode information on optical soliton molecules

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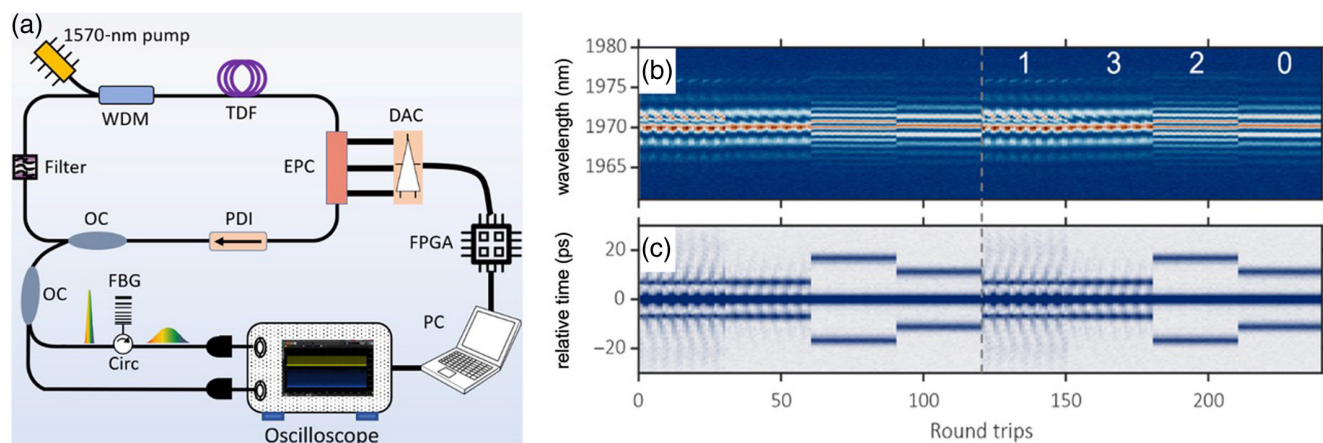
To date, the vast majority of ultrafast laser applications require a stable, unvarying, mode-locked pulsed output. Meanwhile, each year, laser research groups report multitudes of original ultrafast dynamics accessible from relatively standard laser architectures. The richness and universality of ultrafast laser dynamics hinge on the diversity of multiple-pulse regimes combined with a large range of bifurcations.<sup>1</sup> Ultrafast light patterns can self-assemble in a laser cavity, leading, for instance, to soliton molecules, complexes, or crystals. Depending on the system parameters, the dynamics of these light patterns can become stationary or perpetually evolve over consecutive cavity round-trips, following either regular oscillations or chaotic behavior, which affect the internal degrees of freedom of the light patterns, such as inter-pulse spacing, relative phases, and field amplitudes.

Such a great divide between the dynamical possibilities and the practical use of ultrafast lasers is remarkable. A conventional viewpoint considers that a thorough knowledge of ultrafast laser dynamics is valuable because this allows one to better identify and stabilize the stationary single-pulse mode-locked regime sought in applications. However, there can be new practical avenues for non-conventional ultrafast laser regimes. For instance, chaotic pulses may improve the efficiency of communication or sensing systems in a multi-user free-space environment, whereas optical soliton molecules can constitute burst modes of interest in material processing applications.<sup>2</sup> Therefore, there is currently a research and development incentive to move beyond the fixed laser oscillator output and progress toward flexible ultrafast laser sources parametrized through a user-friendly interface.

Another direction is to associate complex dynamics with information encoding. In ultrafast lasers, a multitude of dynamical attractors can be found. For instance, soliton molecule attractors differ by their inter-pulse separations in stationary regimes, and by the amplitude and frequency of their oscillations in pulsating regimes—yes, optical soliton molecules can “vibrate” akin to their matter molecule counterparts! Therefore, a specific accessible subset of robust attractors can be used and linked to a set of information symbols. Rather than propagating information from point A to B, ultrafast lasers can be envisaged as information storage loops and, potentially, optical processors. In 2022, researchers demonstrated quaternary encoding on stationary two-soliton molecules. Switching between the encoding states was obtained through the manipulation of the optical spectrum in the Fourier plane of an intracavity free-space pulse shaper.<sup>3</sup>

Such an attractive prospect has to pass sizeable hurdles. In most situations, there are no known analytic relationships between the features of complex attractors and the laser system parameters, involving a lengthy preliminary trial-and-error search. Moreover, laser dynamics are generally subjected to hysteresis, which complicates the generation of targeted states. Besides, the practical size of ultrafast lasers, which defines the cavity roundtrip time, does not favor high bitrate and capacity, except maybe in the situation of high-harmonic mode-locking.<sup>4</sup>

To address the challenge of reaching a given ultrafast lasing state, assistance from various elementary aspects of artificial intelligence has been tested. In 2015, the first investigation of a “smart laser” employed genetic algorithm (GA) optimization.<sup>5</sup> It was followed by important developments, which were summarized in 2021.<sup>6</sup> GAs, or their closely



**Fig. 1** (a) Representation of the interfaced smart laser developed by Zhou et al. After EA optimization, several soliton molecule dynamics can be reapplied as information symbols, which are characterized by real-time measured optical spectra (b) and corresponding first-order field auto-correlation (c). Adapted from Ref. 8.

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related evolutionary algorithms (EAs), remain among the most powerful techniques to search and find a solution within a complex optimization landscape, despite their relatively long convergence time.<sup>7</sup> Therefore, GA optimization can be efficiently used as an initialization stage to build a library of laser regimes of interest that can be subsequently called by applying the associated laser parameters found by the algorithm.

In their recent publication this year, Zhou et al.<sup>8</sup> realized a technical tour de force in building a smart, compact, interfaced all-fiber ultrafast laser operating in the 2- $\mu\text{m}$  infrared optical region (see Fig. 1). Using various EAs, they demonstrated the possibility of using, as information symbols, not only the stationary soliton molecules but also some of their pulsating dynamics, therefore increasing the potential number of addressable effective symbols. As usual with GA and EA optimization, the most important prerequisite consists of designing appropriate merit functions to effectively condense the perception of the desired laser dynamics from a seasoned laser experimentalist, so that the algorithm performs a useful optimization. Whereas the applied interest of information encoding on ultrafast laser dynamics remains an open question, the development of compact and versatile smart laser

oscillators operating at extended wavelength regions will definitely foster new applicative directions.

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