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Existence of nested oscillators in soliton molecules revealed by Mode Decomposition

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Abstract: Mode decomposition techniques concomitantly reduce noise in data and classify dynamics in term of modes families. Applied to soliton molecules, it reveals that weak oscillators can nest into a principal one, and interact with it. © 2022 The Author(s)

In an ultrafast fiber laser ring cavity, several co-propagating dissipative solitons can interact to form a firmly bound state called a soliton molecule [1]. Soliton molecules exhibit interesting analogy with their chemical counterparts as they can also manifest oscillatory and vibrating dynamics. The existence of the SM, its organization, and its dynamics, are directly related to the internal state of the cavity laser that defines the features of the limit cycle attractor which the SM is attached to [2]. From a fundamental point of view, being able to infer the co-existence of several limit cycle attractors and observe how they impact the SM is of importance as it would provide rich information regarding the internal state of the laser. On a more practical aspect, this would require to measure the weak perturbation undergone by a vibration pattern of a SM; and to be able to analyze more complex vibration pattern, hence beyond the simple two-pulse vibration model.

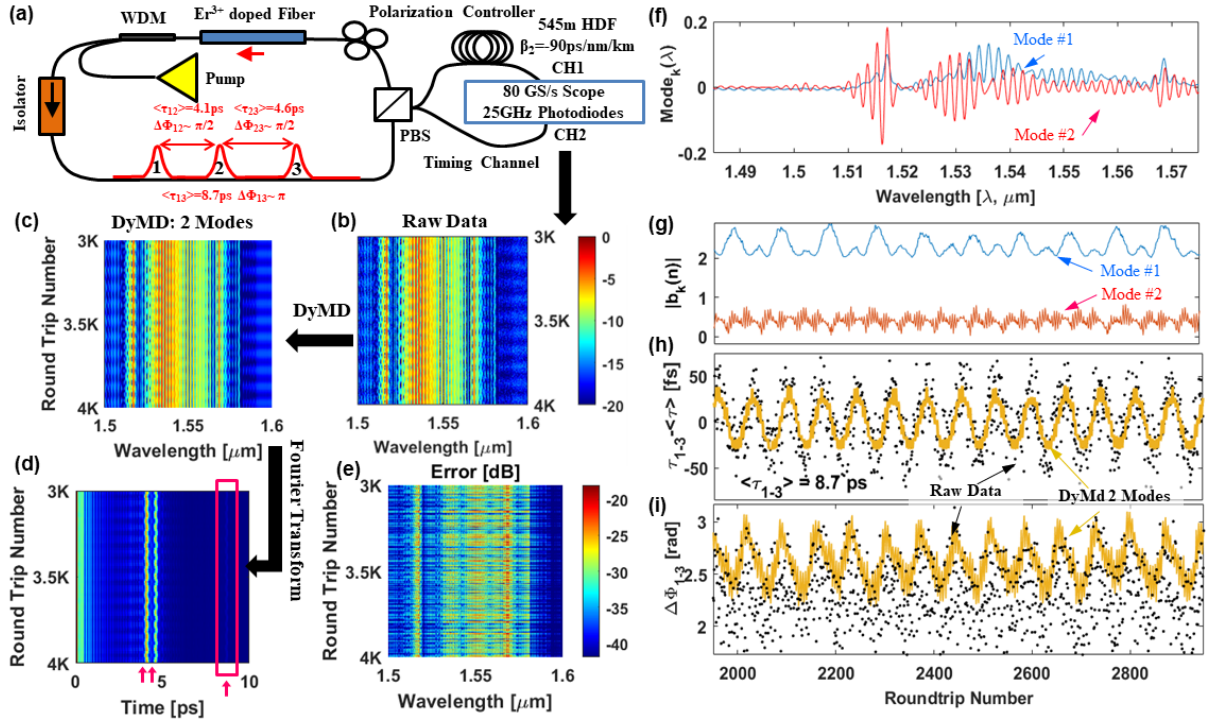


Fig. 1. (a) Experimental setup. PBS: Polarization Beam Splitter. (b) Raw DFT spectra (log scale). (c) DyMD reconstruction of (b) using two Modes. (d) Fourier Transform of (c) showing the three pulses separations (purple arrows). The extracted relative motion of the pulses 1 and 3 (purple frame) is detailed in (h-i). (e) Reconstruction error (in dB) between the DyMD reconstruction and the original dataset. Error below -24dB corresponds to lossless reconstruction. (f) Spectral shape of the modes used for the DyMD. (g) Evolution of their corresponding b_k coefficient. (h) Evolution of the relative separation between the leading and trailing pulses τ_{1-3} . Dots are the untreated data, orange line is the result after DyMD. (i) same as (h), but for the relative optical phase difference.

As an example, we consider here a three-soliton molecule (Fig. 1-(a)) propagating round a 5-m long fiber ring laser cavity comprising 3 meters of Erbium doped fiber and a polarizer (see Fig. 1). Mode-locking is ensured by nonlinear polarization rotation followed by discrimination through a polarization beam splitter, also acting as an output coupler. After dispersion of the laser output in a -50 ps/nm Highly Dispersive Fiber (HDF), the DFT spectra are recorded by an 80GS/s, 40GHz electrical bandwidth, 8-bit depth oscilloscope. This laser architecture can support the propagation of a 3-soliton molecule, characterized by the distinct interferometric fringes seen on the DFT spectra (Fig. 1-(b)).

The trailing and leading dissipative solitons are about π -shifted, hence in a rather unstable configuration. Therefore we expect this soliton molecule to be quite sensitive to its environment, and that the relative motion of the leading and trailing pulse (τ_{1-3}) is the best probe of the external perturbations that could influence the SM. That said $\tau_{1-3} \approx 8.7ps$ is strongly impacted by the bandwidth limitation of the experimental setup, and therefore noise. More globally, the determination of the inter pulse distance and phase (Fig. 1-(d)) is always impacted by noise to some extent. If local fitting and filtering can allow a better determination of the inter-pulse distances, it cannot remove long round-trips to round-trips incoherent drift (low frequency noise). Moreover this method would also filter out fast varying signal, and therefore results in a loss of information. Consequently we decided to perform a Dynamic Mode Decomposition (DyMD [3]) of the DFT spectra (Fig. 1-(d)). It consists in decomposing the instantaneous snapshot spectra $S(\lambda, n)$ at round trip n as $S(\lambda, n) = \sum_k Mode_k(\lambda)b_k(n)$. The temporal dynamics of the laser system is then encoded in the b_k coefficients (Fig. 1-(g)), while the $Mode_k$ contains the information related to vibration mode (Fig. 1-(f)). This decomposition method makes use of the full DFT dataset, hence it is better than local filtering and fitting.

We see first in Fig. 1-(e) that the original DFT data can be decomposed in two modes with less than 1-bit error (note that 8-bit relative precision, namely the resolution of the oscilloscope, corresponds to a -24dB error). In turn, the relative vibration of the two most separated pulses (1-3) can be retrieved with notably higher accuracy than for the untreated data (Fig. 1-(h-i)). This molecule exhibits complex vibration pattern with a principal periodicity of about 71 Roundtrips (RTs). On top of this main oscillation, there exists a riding wave of much smaller amplitude of about 5.2 RTs periodicity. The two vibrations modes are not commensurable with each other. On top of a consequent denoising, the DyMD allows also further analysis through the $Mode_k$ and b_k parameters. Indeed, the b_k indicates that main vibration is supported by the first mode while the second mode encodes the fast oscillation. The b_2 coefficient exhibits a strong modulation at the main vibration period, indicating that it is strongly influenced by the latter. This proves the existence of an interaction between the two oscillations because they cannot be represented by independent combinations/superposition of modes. Secondly, the analysis of the modes shapes (Fig. 1-(f)) shows that they exhibit both interfringes of variable spacing that encodes for the 3 solitons. Consequently each vibration involves the whole SM, not only a part of it. This strongly differs from current descriptions of SM vibration that usually presents the vibration modes as oscillation between pair of solitons (combined with coupled oscillations). Still the mode 2 which describes the fast oscillation has a larger relative weight centered on the third dissipative soliton (FFT of modes not shown here).

The dynamic mode decomposition (DyMD) allows the unambiguous decomposition of vibration modes of complex soliton molecules that involve more than 2 solitons and multiple oscillatory patterns. It also permits a denoising of the raw DFT data with minimal loss of information. In the present proof of concept, we managed to show that a soliton molecule can support two vibration modes, the second one is actually nesting within the principal mode : it acts as a coherent perturbation that is strongly influenced by the main SM oscillation, without having back much influence on the latter. This tends to indicate that the soliton molecule is under influence of radically different attractors. On a more general prospect the current example clearly demonstrates the suitability of the DyMD technique for the analysis of recurring phenomena, which are typical in ultrafast fiber ring cavity lasers.

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