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Fundamental vibration dynamics of soliton complexes in ultrafast fiber laser

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Abstract: Mode decomposition techniques allow decomposing the Dispersive Fourier Transform signal of a soliton molecule in terms of elementary vibration modes. This technique based on correlation permits to aggregate into a global mode the individual evolutions of the pulses which constitute the soliton complexes, hence revealing a much richer dynamics.

In an ultrafast fiber laser ring cavity, several co-propagating dissipative solitons can interact to form firmly bind complexes of pulses called a soliton molecule (SM) [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]. On a practical aspect, the analysis of SM containing more than two solitons becomes much more complex. Indeed it becomes then quite ambiguous to attribute the relative motion of each possible soliton pair to a given oscillator involving the whole molecule. As a result the investigation of large (starting from $N>2$) soliton complexes remains mainly thus far purely descriptive.

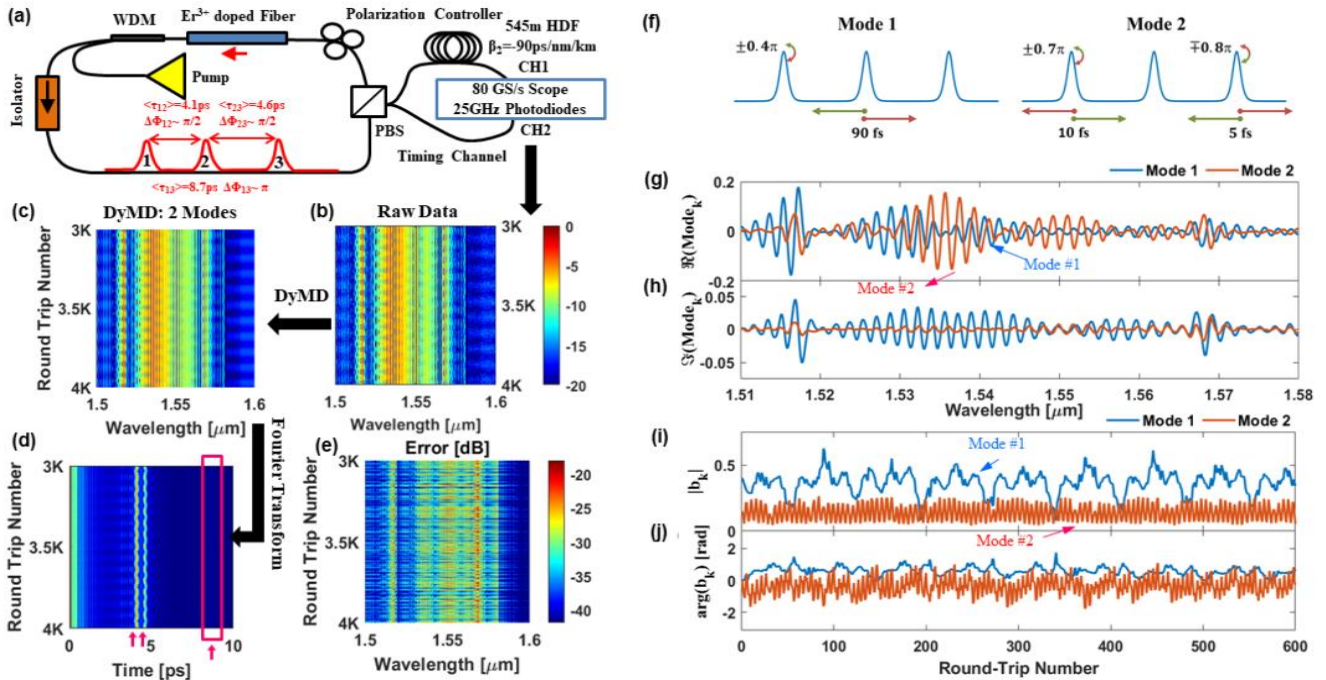


Figure 1 (a) Experimental setup. PBS: Polarization Beam Splitter. (b) Raw DFT spectra (log scale). (c) DyMD reconstruction of (b) using two Modes. (d) Fourier Transform of (c) showing the three pulses separations (purple arrows). (e) Reconstruction error (in dB) of the DyMD decomposition (-24dB is lossless reconstruction). (f) Fundamental vibration mode extracted from the DyMD. (g-h) Relative phase and amplitude evolution between the two modes (b_k coefficients).

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 $S(\lambda, n) = \sum_k \text{Mode}_k(\lambda) b_k(n)$. The temporal dynamics of the laser system is then encoded in the b_k coefficients (Fig. 1-(i-j)), while the $\text{Mode}_k(\lambda)$ contains the spectral information related to vibration mode k (Fig. 1-(g-h)).

As an example, we consider here a three-soliton molecule propagating round a 5-m long fiber ring laser cavity comprising 3 meters of Erbium doped fiber and a polarizer (see Fig. 1-(a)). 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)).

Instead of describing the evolution in term of variation of the individual soliton distance (Fig. 1(d)), the DyMD permits now to describe the dynamics as the interplay of two vibrational modes. The two modes identified within the dataset are presented in Fig. 1-(f): Mode 1 and 2 are odd and even symmetry vibration modes, respectively. Confirming theory regarding soliton interaction, we observe here that for each mode the solitons tend to get out of phase when getting closer, resulting then in a repulsive interaction. Interaction becomes then progressively more attractive (solitons in phase) as the pulses are going away from each other. In addition to the possibility to investigate qualitatively the dynamical features of the soliton molecules, it is also possible to get a more quantitative description. Indeed the amplitudes of each elementary vibration and their relative evolution are encoded in the b_k coefficients (Fig. 1-(i,j)), which are provided by the DyMD along with the modes' shape. We see that the two modes have radically different oscillation frequency and magnitude. In particular, Mode 2 has a period of about 5 Round-Trips and is of low intensity, making it hard to infer without resorting to a proper mode decomposition technics. Regarding Mode 1, its intensity evolves anharmonically with alternated flaring-up and damping burst around an average value of about 0.5. Much fine analysis (not shown here) reveals that the two elementary modes can influence each other, but are otherwise each driven by radically different intrinsic dynamics.

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 in interaction with each other. 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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