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# Long-range synchronization of soliton molecules in fiber ring laser cavity

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**Abstract:** We demonstrate the synchronization of two soliton molecules separated by several nanoseconds in a laser fiber ring cavity. This synchronization is accompanied by inter-molecules oscillations that are locked to the internal motion of the molecules. © 2019 The Author(s)

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The dispersive Fourier transform (DFT) technique permits the observation of the evolution of dissipative solitons in fiber ring laser cavity [1]. During the last few years, an increasing attention has been set on the study of soliton molecules [2]. Soliton molecules consist of two -or more- solitons that strongly interact through the gain medium or cross-phase modulation effects in order to form a bound state [3]. This bound state usually exhibits periodic internal motion that bears analogy with the vibrations properties of linear molecules in chemistry. Recent works consisted in describing the different type of vibrations that can be found such as anharmonic evolution [4], pure phase oscillations [5], oscillation of larger molecules comprising 3 or more solitons [6], etc. Another strong interest in soliton molecules lies in the fact that they are fundamental objects whose generalization could impact the buildup of harmonic mode locking and the stability thereof [7].

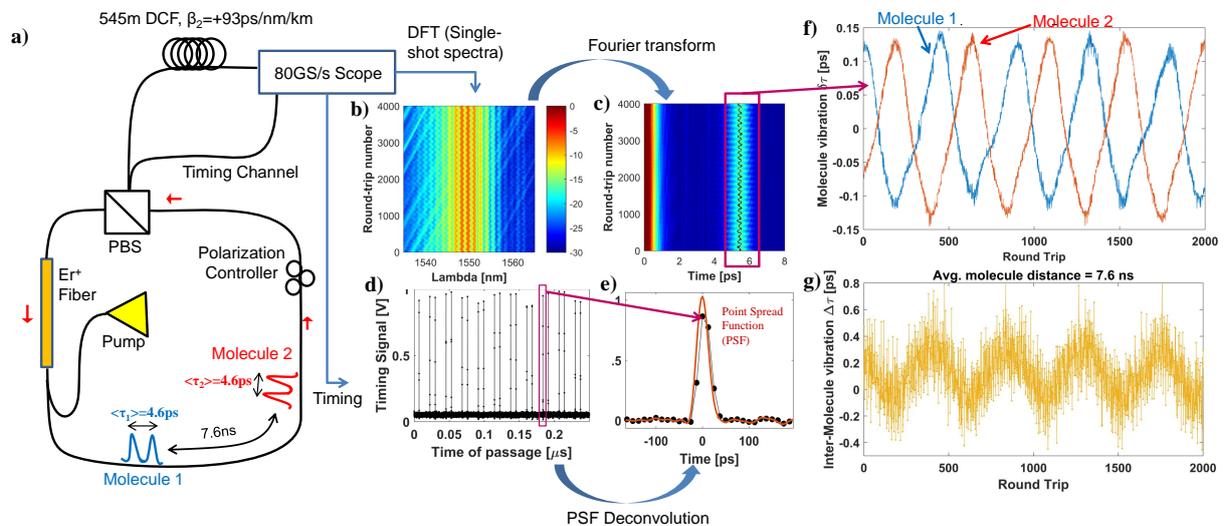


Fig. 1. a) Experimental setup DCF: dispersion compensating fiber. b-c) Recorded single-shot spectra and corresponding auto-correlation trace. d-e) Time of passage of the molecules f) Internal motion of the molecules obtained from c) g) Distance between the two molecules extracted from d-e).

If the DFT technique can resolve the internal motion of a soliton molecule, it does not provide any information about its frequency shifts, nor its global travel speed. As such the interaction between pulses and molecules separated by more than 100ps (e.g. harmonic locking) cannot be observed using this technique; and direct temporal observation using for example a high-speed 80GS/s scope does not allow the observation of subtle sub-picosecond changes in the global motion of the different pulses. In order to solve this issue, we implemented on the temporal traces a deconvolution procedure akin to what is done in fluorescence spectroscopy [8]. Doing so, we managed to get a timing resolution down to about 0.14 ps (100 times lower than the sampling resolution!). Thus we can correlate the internal vibration of the soliton molecule with its external motion around the laser cavity.

In particular, we applied this new technique to the study of the interaction between two soliton molecules [4] separated by 7.6 ns. The fiber ring cavity laser is composed by 1 meter of either Erbium-doped fiber closed by 3 meters of SMF fiber (see Fig. 1-a). The mode-locking is set by nonlinear polarization rotation. One channel of the 80GS/s scope serves for the DFT (internal motion of each molecule), while the second channel serves to observe the global motion of the molecules. Each molecule is composed of two 0.8ps solitons separated by 4.6ps. The vibration of the two molecules is shown in Fig. 1-f.

Firstly, we see that the two molecules undergo the periodic oscillation of 130fs amplitude and 454 Round Trips (RTs) periodicity. In strongly dissipative systems, the properties are fixed by the laser parameters that determine the global attractors [9]; and the periodic internal motion of the molecule may be explained by the existence of an attractor forming a limit cycle for the soliton pair. We see in Fig. 1-f that the 2 molecules have the same dynamics although they are apart by 7.6 ns: the second molecule trajectory is delayed from the first one by about 197 RTs. Such feature remains even in the case of transient irregular motion where both molecules experience the same irregularities. Such behavior suggests that there exists a common limit attractor for the whole cavity.

We then investigated the global dynamics of the two molecules as they circle round the ring cavity (Fig. 1-g). Long-distance repulsion between solitons is ascribed by the recovery dynamics of the gain medium. Interactions can also occur at long distance through noise fluctuations [10]. This contrast with short-distance interaction that comes from direct pulse overlap and dispersive waves [7]. We first observe that the time of passage of the molecules evolves also periodically with same periodicity as the molecule internal vibration. Such a behavior does not exist if only one molecule is present. Remarkably, the two molecules form an oscillating bound state that is synchronized to the molecules internal vibrations.

Consequently we have demonstrated that in a fiber laser cavity there exist couplings between picosecond and nanosecond timescales, so that temporal features that originate from picosecond short range interaction are duplicated on longer distance. These mechanism serves for the synchronization of molecules that are located very far apart (7 ns for a 23 ns round trip). The deconvolution procedure that we used is critical in order to unveil such a subtle long range interactions as they require a very precise timing resolution below 300 fs. In complement to RF analysis, this technique provides new possibility to study the dynamics of multi pulses systems in fiber ring cavity lasers, like harmonic locking.

## Acknowledgement

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