Chaos and synchronization within soliton molecules

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Abstract. We experimentally demonstrate the synchronization of regularly vibrating soliton molecules by means of an injected modulated signal. Such synchronization is analyzed in real time through the sensitive balanced optical correlation technique. We also unveil the existence of chaotic intra-molecular vibrations, to which we successfully apply a similar control strategy. These findings strengthen the hypothesis of internal dynamics of soliton molecules essentially ruled by a reduced number of degrees of freedom, allowing applicative prospects.

1 Internal dynamics of optical soliton molecules: from steady state to chaos

When a laser cavity supports the propagation of several ultrashort pulses, these pulses can form compact bound states called soliton molecules. Soliton molecules are fascinating objects of nonlinear science, presenting striking analogies with their matter molecules counterparts. The relative timing and phase between the copropagating pulses are the most salient internal degrees of freedom of the soliton molecule. Among a wide range of possible pulsation types, optical soliton molecules can exhibit vibrational internal motions, akin to matter molecules (1,2,3). For temporal soliton molecules, this means that the relative timings between the traveling pulses that make up the molecule will oscillate. These oscillations are intrinsically nonlinear and can be highly anharmonic.

These features led us to experimentally discover, in the case of a 2-soliton molecule, also called a soliton pair, the existence of chaotic internal dynamics (3). We reached chaotic dynamics following the typical period-2 bifurcation cascades that are ubiquitous in nonlinear physics and dissipative soliton dynamics (4). Such observation of chaotic soliton molecule follows an earlier theoretical prediction (3) and is linked to the existence of a strange attractor. Figure 1 presents a qualitative picture of the central internal dynamics of a soliton pair molecule, namely: the stationary soliton molecule that is associated to a fixed-point dissipative soliton attractor, the regularly vibrating soliton that follows a limit cycle attractor, and the newly discovered chaotic soliton molecule that corresponds to a strange attractor. In these experiments, the relative temporal separation between the two pulses that make up the soliton molecule is measured through the balanced optical correlation (BOC) scheme. BOC is a sensitive characterization technique allowing to follow in real time, with MHz bandwidth, the fluctuations and/or oscillations of inter-pulse separations (6). We found that such characterization technique was well adapted to the study of internal soliton molecule vibrations, as BOC combines real time monitoring of physically clear signals (i.e., obvious information without complex postprocessing) and a high temporal resolution to follow up of the relative separation at the femtosecond level.

Fig. 1. Schematic diagram of the real-time characterization of the temporal extension of dissipative optical soliton molecules. (a) The soliton molecules with diverse internal dynamics are generated by a mode-locked fiber laser and sent into the BOC measurement. (b) An S-shaped curve is obtained when the delay between the two arms is scanned, which allows to define a linear measurement range (red-dotted line). (c) We measure three different types of intra-molecular dynamics: stationary states with a fixed separation, vibrating states following a regular oscillation, and chaotic states characterized by unpredictable separation dynamics. They respectively correspond to: fixed points, limit cycles and strange attractors of the effective dynamical system. OSC: oscilloscope. ESA: electric spectrum analyzer.

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2 Control and synchronization of the internal dynamics of a soliton-pair molecule

Since the characteristic frequencies of these oscillations are sensitive to the laser system parameters, we see an opportunity to control the internal dynamics of soliton molecules. We experimentally demonstrate the synchronization of the internal vibrations of soliton molecules through the optical injection of a modulated signal inside of the laser cavity. This modulated signal serves as a master oscillator whose frequency and modulation strength are carefully adjusted. The principle of the experiment is sketched in Fig. 2(a). Following the general features of the synchronization theory, we found that the main frequency component of the vibrating soliton molecule could be locked to the master oscillation frequency.

(a) EDFA Func. Gen. CW EOM fs-Laser
(b) Slave Frequency (kHz) vs Drive Frequency (kHz)
(c) BOC Output (100 fs/div) vs Time (μs)

Fig. 2. (a) Illustration of the principle of control of the internal dynamics of a soliton molecule through an injected modulated signal. CW: continuous laser source, EDFA: erbium-doped fiber amplifier, EOM: electro-optic modulator. (b) Example of synchronization obtained on a regularly vibrating soliton molecule, highlighting the synchronization locking range when the drive (master oscillator) frequency gets in the vicinity of the internal (slave) frequency. (c) Illustration of chaos control when the injected modulated signal is increased, from lower to upper plot. At an injection power of 9.2 mW, the dynamics becomes perfectly regular. The transition is reversible when the modulation level is subsequently decreased. From Ref. 3.

The extension of the locking range increased as a function of the master oscillator amplitude until some practical limits, which is a dynamical phenomenon portrayed by the so-called “Arnold tongues”. An example of the synchronization of the internal vibrations of a soliton-pair molecule is shown in Fig. 2(b) (Ref. 4). In our experimental studies, we verify that the soliton molecule remains a robust entity with respect to the injection signal, which means that the integrity of both pulses and their average separation remain hardly affected. This is possible since the vibration amplitude stay much smaller than the inter-pulse average separation.

Finally, we investigated control strategies of the soliton relative motion in the case of molecules featuring chaotic internal dynamics. We first showed that increasing the optical power of the laser pump enabled a sequence of bifurcation leading to chaotic internal motion. Conversely, by reducing the pump power, the chaotic dynamics transitioned to a regular oscillatory motion. Then, we demonstrated an all-optical control of the chaotic dynamics through external optical injection, featuring a fast error-free switching between regular and chaotic soliton molecule vibrations. This is illustrated in Fig. 2(c).

The fast error-free switching between ordered and chaotic soliton molecules enabled by pump current sweeping and external injection highlights the potential prospects of all-optical logic gates and chaotic communication using soliton molecules.

References