Research article

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Real-time dynamics of soliton collision in a bound-state soliton fiber laser

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Abstract: We experimentally investigated the soliton collisions between soliton molecules and deuteronogenic solitons spontaneously generated on the continuous wave (cw) noise background in an ultrafast erbium-doped fiber laser mode locked with MoS₂ saturable absorber (SA). The dynamics of the soliton collisions were observed using the time-stretch dispersion Fourier transform technique. The noise-induced deuteronogenic solitons first undergo spectral broadening and wavelength shifting, then collide successively with a soliton molecule and eventually vanish. Within the simple collision framework, the spectral-temporal dynamics of soliton collision would help to unveil the self-stabilization mechanism of the soliton molecules in consideration of dispersive wave shedding. This nonlinear dynamics is similar to the soliton rain, except that complex condensed soliton phase is substituted with a soliton molecule.

Keywords: molybdenum disulfide; soliton molecule; soliton collision; time-stretch dispersive Fourier transform.

1 Introduction

Dissipative solitons (DSs) are localized structures appearing in a dissipative system that is far from equilibrium and exchanges energy and matter with the surrounding environment [1]. The concept of DSs provides a general model to interpret complex nonlinear dynamics in different fields, such as hydromechanics [2], Bose-Einstein condensate [3], granular media [4], nonlinear optics [5], etc. Passively mode-locked fiber lasers (PMLFLs) are a typical dissipative system. In PMLFLs, a number of DSs usually tend to be self-organized on noise floor and converge to the attractors formed by a composite balance between nonlinearity, dispersion, linear and saturable loss, and bandwidth-limited gain. These DSs interact with each other through various mechanisms, such as direct coherent overlapping of pulse tail, dispersive wave, optomechanical effect, slow depletion and recovery processes of the gain, quasi-continuous-wave (cw), Casimir-like forces, etc. Therefore, DSs can form composite patterns in both global and local ranges, such as soliton molecules, harmonic mode locking, and exhibit abundant dynamic phenomena, such as soliton pulsation [6], soliton explosion [7, 8], soliton rain [9, 10], and chaotic noise-like pulses [11]. Obviously, PMLFLs provide an ideal platform to investigate the formation, evolution, and annihilation processes of DSs and understand the self-organization mechanism in complex dissipative systems [12].

Soliton rain is an attractive DS dynamic phenomenon, which involves formation, drift, collision, and annihilation of DSs and is analogous to the cycle of water in nature [13]. When the soliton rain occurs, there are three coexistent components in PMLFL: quasi-cw components, drifting solitons, and condensed soliton phases. The drifting solitons are stochastically born in the noise background constituted by quasi-cw components, and then drift until they crash into a condensed soliton phase. At the same time, the condensed phase radiates energy to maintain its total energy constant. The condensed phase that consists of bound solitons usually spans several hundred

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picoseconds and has a large internal timing jitter. Therefore, experimental observation of its internal details is rather difficult. In previous studies, it was hypothesized that the solitons that make up the condensed phase are identical to the drifting solitons. Recently, the drift of DSs through Casimir-like interaction was discovered [14]. However, the details of the growing process of drifting solitons and its interaction with the condensed phase were rarely studied.

Time-stretch dispersive Fourier transform (TS-DFT) technology, which is based on wavelength-to-time mapping for localized optical pulses using group-velocity dispersion, provides a powerful method to observe the transient dynamics of optical solitons [15]. Therefore, the TS-DFT technology renewed the interests in DSs dynamics of PMLFLs [16–18]. The TS-DFT technology was employed to investigate the noise-like pulse, soliton explosions, and soliton pulsation [19]. More recently, this technology was used in the field of soliton molecular dynamics [20, 21]. By performing Fourier transform on the amplitude of the single-shot spectra of TS-DFT, autocorrelation traces can be obtained to analyze the internal dynamics of the soliton molecules [22]. This method was also used to investigate the DSs inherited from noisy quasi-cw floor during self-started mode-locking processes [23, 24]. However, TS-DFT was not applied to the observation of those phenomena similar to soliton rain.

In this work, we demonstrate simplified soliton rain dynamics in a MoS_2 SA-based PMLFL. Compared with the

conventional soliton rain, a soliton molecule replaces the condensed phase and collides with the deuterogenic solitons (drifting solitons) caused by the noisy quasi-cw in the PMLFL. By using the TS-DFT technique, we investigated the spectral-temporal dynamics of the soliton molecule, deuterogenic solitons and their collision. We find that the deuterogenic solitons would experience two stages of accumulation and acceleration in their initial evolution period. When a collision occurs, the deuterogenic soliton vanishes, and the soliton molecule exhibits self-stability by radiating dispersion wave. It is interesting to note that the energy of the solitons that make up a soliton molecule is significantly higher than that of the deuterogenic solitons, which means they correspond to different attractors in the dissipative system. These findings provide a unique insight into the internal evolution of soliton collision and enrich the ultrafast transient dynamics of nonlinear systems.

2 Experimental setup

A schematic diagram of the experimental loop is sketched in Figure 1. The laser employed in our experiment is an anomalous dispersion passively mode-locked erbium-doped fiber laser (EDFL) composed by a 2-m erbium-doped fiber (EDF) and a 13-m-long single-mode fiber (SMF) with respective group velocity dispersions (GVDs) of $40 \text{ ps}^2/\text{km}$ and $-23.9 \text{ ps}^2/\text{km}$. The corresponding net dispersion is about

Figure 1: Schematic diagram of the experimental setup for the MoS_2 SA-based mode-locked fiber laser.

-0.23 ps^2 . The gain fiber is pumped by a 980-nm laser diode (LD) through a 980/1550-nm wavelength-division multiplexer (WDM). In addition, a polarization-independent optical isolator (PI-ISO) ensures unidirectional lasing. A polarization controller (PC) is utilized to tune cavity birefringence, and the optical couplers (OCs) are employed to split the mode-locked pulses. Mode locking is passively achieved by a MoS_2 -deposited microfiber. Few-layer MoS_2 -based SAs provide virtual, efficient broadband saturable absorption effect, and high nonlinearity, which allows for the multiple-soliton state to acquire the soliton collisions in a traditional EDFL under low pump power. Moreover, sufficient ultrafast dynamics were observed in the MoS_2 SAs-based EDFLs [25–29]. Note that in a previous work, we found that the MoS_2 SA-based ultrafast fiber laser could supply a stable soliton molecule with simple components [30], which is suitable to serve as an anchor to set up the collision framework so that the detailed features of soliton collision could be investigated in this work.

To achieve the DFT real-time measurement on a shot-to-shot level, the laser output is temporally stretched by a 1-km-long dispersion compensation fiber (DCF) with the dispersion of -150 ps/km/nm . The temporal optical intensity is detected by a 50-GHz photodiode (U2TXPDV2120R, U2T, Germany) and evaluated by a 36-GHz oscilloscope (LCRY3312N69578, LeCroy, Chestnut Ridge, NY, USA). The averaged spectrum and the pulse separation are measured using an optical spectrum analyzer (OSA, AQ6370C,

Yokogawa, Japan) and an auto-correlator (FR-103XL, Femtochrome, Berkeley, CA, USA), respectively.

3 Results and discussion

The entire process of simplified soliton rain dynamics experiences three different stages, i.e. soliton molecule (anchor), evolution of deuteronogenic solitons, and the final collision and dissipation. Note that the deuteronogenic solitons are similar to drifting solitons in conventional soliton rains, but it is difficult to observe their dynamics through a low-speed oscilloscope. Furthermore, the deuteronogenic solitons are formed after the soliton molecules by properly adjusting the polarization state in the laser cavity. So this type of solitons is named as deuteronogenic solitons in this work. Thanks to the TS-DFT technique, these three stages are demonstrated orderly in both the time and spectral domains to expose the internal dynamical evolutions.

3.1 Soliton molecule

With the increment of pump level, the laser states switch from traditional mode-locking operation to the bound-state harmonic mode-locking operation. The averaged spectrum of the harmonic mode-locking state of bound solitons is shown in Figure 2A. Obviously, the phase

Figure 2: The bound-state harmonic mode-locking operation at a pump power of 105 mW. (A) the averaged spectrum; (B) pulse train; (C) auto-correlation trace.

difference between soliton molecules is roughly π . In addition, according to the relationship between the pulse separation and modulation period:

$$\Delta T = \lambda_0^2 / (c \cdot \Delta \lambda_0) \quad (1)$$

where ΔT is the pulse separation of the soliton molecule, λ_0 is the central wavelength, c is the speed of light in vacuum, and $\Delta \lambda_0$ is the modulation period. According to the spectroscopic data of Figure 2A, λ_0 is about 1562.3 nm, and $\Delta \lambda_0$ is about 1.58 nm. Therefore, the pulse separation of the soliton molecule can be calculated to be 5.15 ps. The corresponding pulse train is depicted in Figure 2B, during the single-cavity round-trip time of 76 ns, 62 bound-state pulses with a separation of 1.23 ns occupy the whole laser cavity with the same central wavelengths, and therefore, soliton collision dynamics cannot be achieved by the equidistant unmovable bound-state pulses. The corresponding auto-correlation trace shown in Figure 2C has three peaks with an intensity ratio of 1:2:1, indicating that the two solitons in the bound state pulses have the same intensity. Moreover, the soliton separation from the AC trace is measured to be 5.14 ps, which is very close to the calculated value.

In order to build up the multiple-soliton state to investigate soliton collision dynamics, the injected pump power is fixed at 105 mW, and the laser polarization state is adjusted by a PC. Interestingly, we find that the orientation variation of the PC will trigger off the appearance of a cw component. Moreover, within the single cavity round trip time, the number of soliton molecules decreases to two, while many deuterogenic solitons substantially pop out of the noisy background in the temporal domain. Figure 3A and B exhibits the eventual spectrum and pulse train of the stable coexistence state composed by soliton molecules and deuterogenic solitons under the specific settings of the PC. Compared with the bound-state harmonic mode-locking operation, the optical spectrum of the coexistence state is more complicated due to the closely apart central wavelengths of the soliton molecule and deuterogenic solitons. As shown in Figure 3A, the central wavelength of the deuterogenic soliton is obviously located on the left side of that of the soliton molecule, causing the distinction between group velocities. Therefore, the soliton molecule and deuterogenic solitons are about to collide with each other.

Because of the low drift rate, it is not easy to capture the soliton collision dynamics at the pump power of

Figure 3: Composite regime of soliton molecules and deuterogenic solitons.

(A) Optical spectrum measured by OSA under a pump power of 105 mW; inset is a typical single-shot spectrum of soliton molecule.

(B) Pulse train. (C) The spatio-spectral evolution of soliton molecule based on the TS-DFT technique.

105 mW, which is important to, respectively, trace the spectral evolution of soliton molecule and deuterogenic soliton. Based on the TS-DFT technique, the experimentally observed real-time spectral evolution of the soliton molecule in coexistence state is depicted in Figure 3C, and the numerical mapping from temporal domain to spectral domain could be conducted using the following relationship [22]:

$$\Delta t = |D|L\Delta\lambda \quad (2)$$

where Δt is the time spacing after stretch, D and L , respectively, refer to the dispersion parameter and length of the DCF, $\Delta\lambda$ is the spectral bandwidth. Herein, D is about -150 ps/km/nm, and L is about 1 km. As shown in Figure 3C, the time spacing between the outboard distinguishable modulated spectrum is measured to be 2.03 ns, and the corresponding spectral bandwidth is calculated to be 13.53 nm, which is in excellent agreement with the labeled interval of the time-averaged optical spectrum in Figure 3A. The inset in Figure 3A shows a single-shot spectrum of the soliton molecule at a round-trip of 500, showing that three modulation periods are located near the central wavelength, and the phase difference between the soliton molecule is π .

The energy of the soliton molecule is considerably greater than that of the deuterogenic solitons (see Figure 3B), and therefore, they correspond to different attractors in the dissipative system. The autocorrelation trace of the coexistence state is depicted in Figure 4A. Note that the ratio of the main peak to the side peak is different from that of the bound-state harmonic mode-locking operation. The difference is caused by the coexistence of the two types of solitons in the cavity, which was previously discussed in Ref. [31]. Moreover, compared with the bound-state harmonic mode-locking operation, the pulse separation of the soliton molecule

in coexistence state reduces to 1.87 ps. In addition, the autocorrelation traces basically remains unchanged with the increment of pump power, as depicted in Figure 4B, showing stronger inherent stability of the soliton molecule in coexistence state. Assuming that the pulse separation of the soliton molecule in coexistence state is 1.87 ps, the modulation period is calculated to be 4.35 nm according to Eq. (1), implying that three modulation periods are within the labeled interval of 13.1 nm in Figure 3A, which is also in good accordance with the aforementioned estimations. The stable soliton molecule could be used as an anchor to provide a mobile reference frame for monitoring the evolution of deuterogenic solitons and the subsequent soliton collision dynamics.

3.2 Evolution of deuterogenic solitons

To give an intuitive impression on the evolutionary process of deuterogenic solitons, a magnified three-dimensional spatio-temporal representation (i.e. time domain evolution) with the cavity temporal interval from 68.3 ns to 70.6 ns is depicted in Figure 5. By tracking the drift motions, we find that the deuterogenic solitons would experience two stages before maturity, including accumulation dynamic stage and acceleration dynamic stage, as respectively

Figure 5: The spatio-temporal evolution of the deuterogenic solitons.

Figure 4: The autocorrelation trace of the coexistence state at (A) 105 mW; (B) 200 mW.

In addition, the autocorrelation traces basically remains unchanged with the increment of pump power, as depicted in Figure 4B.

depicted in the dashed ellipses of Figure 5. During the accumulation stage, the energy of the deuterogenic soliton is gradually increasing, while the drift rate (calculated by the proportion between temporal position and round trip) remains unchanged, which can be attributed to the following reasons in consideration of Q-switched fluctuations of the laser cavity with cw component: a noisy, chaotic background with significant fluctuations would be induced by the cw component and then be amplified by the efficient broadband saturable absorption effect of MoS₂ SA and the gain amplification effect of EDF [13].

When a certain energy threshold is reached, the deuterogenic soliton will enter the acceleration dynamic stage. During this stage, the drift rate of the deuterogenic soliton goes up significantly, which can be manifested by the bending trajectory, and then, all the deuterogenic solitons tend to be mature and drift with the same rate eventually, i.e. the state of solitons turns into mode-locked operation. When the motion trails of different deuterogenic solitons intersect with each other, such as snapshots A and B, the soliton fusion, apart from the superposition of pulse energies at the intersections, cannot be observed, and in this case, the drift behaviors are speculated to be regulated by the Casimir-like interactions [14]. It could be seen that the spatio-temporal diagram exhibits the drift tendency of the deuterogenic soliton, which would be valuable to reveal the intrinsic evolutionary mechanism.

Figure 6 illustrates the real-time spectral evolution of the deuterogenic solitons based on the TS-DFT technique. Note that it is rather difficult to implement the numerical mapping from temporal to spectral domain (i.e. transformation between time spacing and bandwidth of the optical spectrum) for deuterogenic solitons because we do not have information on spectral characteristics, and multiple deuterogenic solitons are simultaneously present in the cavity with overlapping spectra. Alternatively, according to the temporal evolution, the spectral evolution should go through two stages as well. As depicted in the white dashed circle, a series of jitters turn up in the energy accumulation stage with “Λ” shape spectral broadening for the juvenile of deuterogenic solitons, which is caused by the self-phase modulation (SPM) effect [32] that induces a nonlinear phase shift to stretch out the spectrum without wavelength shifting [33]. Subsequently, the spectrum expands rapidly, accompanied by the shift of central wavelength. The transient dynamics of wavelength shift was reported in Ref. [16] and ascribed to the asymmetrical spectral broadening [32]. The wavelength shift will change the group velocity of the deuterogenic soliton and cause variation in drift rate, as shown in spatio-temporal diagrams.

Figure 6: Spatio-spectral evolution of the deuterogenic solitons based on TS-DFT technique.

3.3 Soliton collision and dissipation dynamics

By boosting the pump power to 200 mW, the spatio-temporal evolution of the collision dynamics can be efficiently captured. As shown in Figure 7A, all of the mature deuterogenic solitons drift at the same velocities, two of which collide with the soliton molecule near the round-trips of 1848 and 5457, and then disappear. For simplicity, we focus on the spectral-temporal dynamics of the second collision due to the same evolutionary characteristics.

The spatio-spectral evolution of soliton collisions measured by single-shot DFT is depicted in Figure 7B. The short-wave spectrum of the soliton molecule is distorted by the deuterogenic soliton, and the long-wave spectrum does not seem to be affected. However, by magnifying the spectral view of the second collision in the blue dashed rectangle, a set of spectral fringes emerge on the whole spectrum of the soliton molecule after the impact, as shown in the bottom inset of Figure 7B. Therefore, the mutual interaction between the soliton molecule and deuterogenic solitons can be divided into collision dynamics and dissipation dynamics.

In the collision stage, spectral fringes appear in the left spectrum of the soliton molecule, and the spectral fringe density decreases with the round trip number, which can be interpreted by central wavelength offset

Figure 7: The spectral-temporal dynamics of soliton collision.

(A) Spatio-temporal map of soliton collision at a pump power of 200 mW. (B) Corresponding spatio-spectral evolution based on TS-DFT technique; bottom inset: the zoom-in spectral view. (C) Field autocorrelation of each single-shot spectrum.

of the soliton molecule with respect to the deuterogenic soliton As depicted in Figure 3A, the central wavelength of deuterogenic soliton is located in the short-wave spectrum of the soliton molecule. During the collision process, the separation of the soliton molecule and deuterogenic soliton decreases gradually, which leads to the spectral fringe density change. After the collision, the deuterogenic soliton is devoured, and the energy of the soliton molecule increases accordingly. The soliton molecule would release one part of the energy to reshape to its steady state. Meanwhile, temporal phase perturbations would be imposed on the solitons through cross-phase modulation (XPM) during the collision process [34]. Consequently, the DW would be triggered to interfere with the soliton molecule and causes the symmetrically distributed modulation fringes in the dissipation stage. The modulation depth of the spectral fringes in the dissipation stage decreases gradually, which implies the decay of the collision-induced DW, and the soliton molecule would evolve toward its stable state for the next collision. The

single-shot spectrum of Figure 7B is then Fourier transformed to acquire the field autocorrelation [22], which can exhibit the pulse separation between successive solitons, as shown in Figure 7C. Obviously, the pulse separation of the soliton molecule maintains unchanged throughout the collisions, which may be attributed to the following two factors: the first is the great disparity in soliton energy, and the second is that the same drift rates of deuterogenic solitons ensure the collisions occur one by one to keep the stability of the bound state.

Owing to the self-stabilization of the soliton molecule and the normative evolution of the deuterogenic soliton, soliton collision can occur continuously, which is similar to the soliton rain dynamics [35]. However, the structural component of the soliton molecule is simpler than when in the condensed soliton phase, and thus, the spectral-temporal dynamics during the collision process can be easily traced. In the case of the conventional soliton rain dynamics, the structural component of the condensed soliton phase is so complicated that

the condensed soliton phase and drifting soliton are assumed to be derived from the same attractor, and the number of solitons in the condensed phase can be calculated by the ratio of the energy of the condensed phase to that of an isolated drifting soliton in dissipative systems [13]. However, as to the simplified soliton rain dynamics presented in this work, we find that the soliton molecule and deuteronogenic soliton are correlated with different attractors, indicating that different localized attractors can coexist in the same dissipative system, and the number of solitons in the condensed phase may no longer be simply calculated by the energy ratio in this case.

4 Conclusions

In conclusion, the entire process of soliton collision dynamics of a MoS_2 -based bound-state soliton fiber laser was investigated in both temporal and spectral domains using the TS-DFT technique. After a series of generation, energy accumulation, and acceleration stages, the deuteronogenic solitons would drift at the same rate to collide with the stable soliton molecule. In addition, the reconstructed spectral evolution was implemented to study the dynamic soliton-dispersive wave interference. The experimental work conducted in this paper shows the self-stabilization of soliton molecule and may provide an insight into the intricate dynamic evolution of conventional soliton rain.

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