Observation of Soliton Molecules in a Dispersion-Managed Dissipative Fiber Laser System

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Abstract
In this study, the experimental observation of stable soliton molecules in a dispersion-managed dissipative fiber laser system employing a MoS_2-based saturable absorber is reported. The laser cavity, designed with a thulium-doped fiber gain medium and dispersion-shifted fibers, generates bound pulse pairs at 1.9 μm with a constant inter-pulse separation of 1.7 ps. Real-time dispersive Fourier transform measurements reveal periodic vibrational dynamics, manifested as coherent oscillations in both temporal separation and relative phase between constituent solitons, mimicking the behavior of chemical molecules. This robust dynamical stability over thousands of cavity round trips demonstrates the potential of soliton molecules for advanced applications in ultrafast optical communications and photonic logic processing.

Keywords: Soliton molecules; Fiber lasers; Dispersion-managed dissipation; Autocorrelation
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1. Introduction

Ultrashort laser pulses are the fundamental of many modern scientific and industrial applications such as ultrafast optical communications, precise materials processing, and spectral and optical measurements [1-6]. With the rapid development in laser technology, the dispersion-managed dissipative fiber laser (DMDFL) provides an optimum platform to generate high-energy pulses with exceptional stability due to dynamic balance between energy, loss, chromatic dispersion, and photonic nonlinearity [7-10]. At the core of such systems, a unique physical system known as "soliton molecules" exists. This system is an inspired simile from molecular chemistry as two or more pulses of solitons are correlated together via firm optical bonds to form a stable structure [11-14]. They are seen as a real molecule oscillating and rotating in the spatial phase [15-18].

Understanding the formation mechanism of such photonic molecules, controlling them, and monitoring their interactive modes represent a drastic scientific challenge and fertile research field since they are not limited to disclose complex nonlinear behaviors only but extended to employ such systems in promising applications like multilevel optical cryptography, photonic logic processing, and increasing information transfer capacity to new levels [19-24].

Such systems are fundamentally based on the incorporation of dispersion control elements into fibers with alternating scattering signatures to allow preparing the system to maintain the phase of solitons constituting the molecule [25-30]. Despite the advancement in modeling and simulation of such systems, still there are major questions about stability limits, phase exchange mechanisms, and effect of environmental noise on the internal cohesion of soliton molecules, and these questions require accurate experimental and theoretical answers.

Consequently, this work aims to deeply explore the phenomenon of soliton molecules in the advanced laser system throughout the precise design of the laser cavity, high-accurate spectroscopic analysis, and self-measuring techniques in order to decode the dynamic language of these photonic entities and know more about their revolutionary possibilities for the future of photonics.

2. Experimental Part

In order to accurately measure the formation and development of soliton molecules in the DMDFL, a monodirectional ring cavity was constructed as shown in Fig. (1). A 980-nm semiconductor laser with maximum power of 700 mW was used as pumping source through a 980/1950 nm wave demultiplexer (WDM) to pump the thulium-doped fiber of 1.3 m length to operate at the fundamental wavelength of 1.9 μm to provide gain in the near- and mid-infrared (NIR and MIR) regions.

To ensure polarization uniformity and prevent undesired back reflections, polarization-insensitive optical isolators (PI-ISO) were incorporated at the entrance and exit ends of the active fibers. To manage the total chromatic dispersion of the cavity, dispersion-shifted fibers (DSF) of 50 m length with two single-mode fibers (SMF-28) each of 10 m length. This creates a dynamic balance between the positive and negative dispersions and hence enables the system to reach close-to-zero dispersion or accurately-managed system. To select the spectrum and maintain the central wavelength at 1950 nm, three matched spectral filters (SF) with 10 nm bandwidth were inserted and distributed along the cavity to support the spectral purity and prevent the generation of sideband wavelengths. The fundamental element of saturable absorber and negative mode locking achievement is MoS_2 nanoplates mounted between the two ends of the fibers via a mechanical junction to allow fast-responsive nonlinear absorption that participates to the formation of ultrashort pulses.

To allow the required measurable part, an output coupler (OC) of 90:10 ratio was used as 10% of the input laser intensity is extracted and directed to the measurement system, while the remaining 90% is returned back to the cavity to keep continuous generation. The temporal development of soliton molecules is measured by monitoring the relative time separation (τ) and relative phase (φ) between solitons constituting the molecule using the cross-correlation frequency-resolved optical gating (X-FROG) technique and spectral coherence analysis, dynamic response recording at different pumping powers to study the stability limits and decomposition and recombination conditions of photonic molecules.

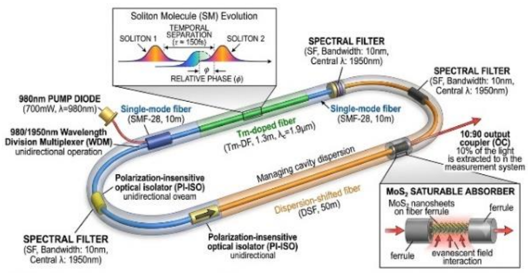

Fig. (1) Dispersion-managed dissipative fiber laser cavity for soliton molecule observation

3. Results and Discussion

Figure (2) explains the optical spectra evolution with modulation fringes as they show magnified marginal interference with time separation (Δλ) of 1.6 nm, which is directly converted into inter-pulse separation (Δτ) of 1.7 ps that confirms the formation of dual soliton molecules inside the cavity. The comparison with the single-pulse state reveals the absence of these fringes, which confirms that the spectral interference is a fingerprint for the cohesive bonding between solitons. As well, the dependence on pump power explains the transformation and stability of fringe intensity within a limit pumping range as the molecule decomposes when exceeding a specific threshold and hence determining the stable operating window to generate these photonic molecules [31].

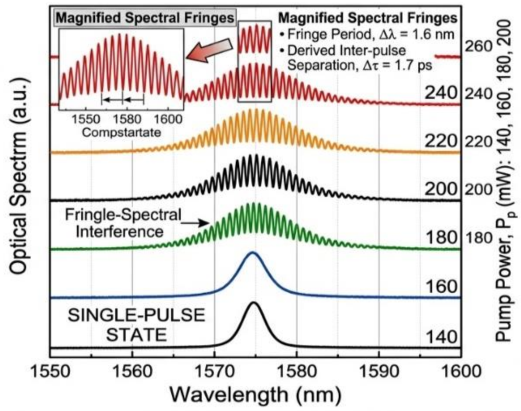

Fig. (2) Optical spectra evolution with modulation fringes

In Fig. (3), the autocorrelation trace showing bound pulse pairs is shown as the magnified autocorrelation peaks exhibit constant tile separation (Δt) of 1.7 ps between the two solitons constituting the molecule regardless the variation of gate potential in the laboratory range. Also, the full-width at half maximum (FWHM) is about 300 fs that confirms the ultrashort nature of each single pulse. When these results were compared to the single-pulse state, there were no secondary peak at all, which reveals that the dual structure is an exclusive consequence of the formation of a coherent soliton molecule and the inter-pulse separation is being stable and not affected by the variations of operation conditions within the stability window [32].

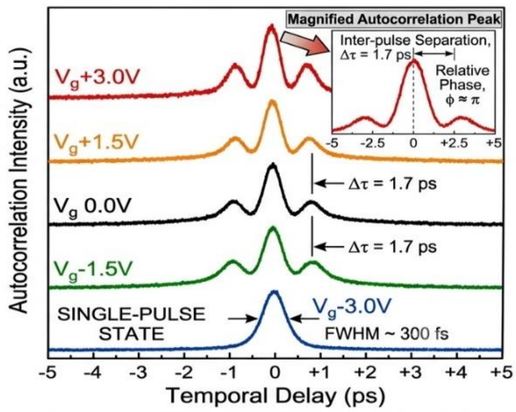

Fig. (3) Autocorrelation trace showing bound pulse pairs

4. Conclusion

The experimental results revealed the possible generation of stable and coherent soliton molecules in a dispersion-managed fiber laser system using a saturable absorber based on MoS_2 as a constant time separation of 1.7 ps was observed between the two solitons constituting the molecule. As well, the measurements explained periodic vibrational dynamics in terms of time separation and relative phase with the number of cavity trips to simulate the behavior of chemical molecules.

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