Real-Time Explosion Dynamics in a Thulium-doped Linear Fiber Laser

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Abstract: Real-time explosion dynamics in a transition chaotic state and a dual-wavelength vector soliton state in a thulium-doped linear fiber laser are analyzed with real-time pulse measurements.

1. Introduction

Soliton explosions are one of the most fascinating nonlinear phenomena in ultrafast laser systems, since pulses can experience abrupt spectral collapse and afterwards return to their original shape [1]. While most studies on real-time dynamics of soliton explosion in the past have been conducted in erbium or ytterbium baser fiber laser systems [2,3], here, we present explosive event in a transition state between single-pulsing and doubling pulsing and collision induced explosion in a polarization-multiplexed dual-wavelength state in a thulium (Tm)-doped fiber laser system for the first time, to the best of our knowledge.

2. Experimental Results and Discussion

Dispersive Fourier transform (DFT) has enabled real-time measurements of both spectral and temporal information in ultrafast lasers to unveil underlying transient dynamics. Due to high propagation losses for wavelengths around 2 µm in standard passive silica fibers, a modified DFT setup relying on up-conversion of the 2 µm light to 1 µm via second harmonic generation (SHG), cf. Fig. 1, is utilized to capture the real-time pulse dynamics. A linear mode-locked Tm-doped fiber laser with a net anomalous cavity dispersion (see [4]) is studied. The pulses are first amplified in a home-built thulium-doped fiber amplifier to ensure sufficient power for SHG. The frequency-doubled light is stretched in a SMF fiber spool to perform DFT and is converted to an electronic signal and recorded with a fast oscilloscope.

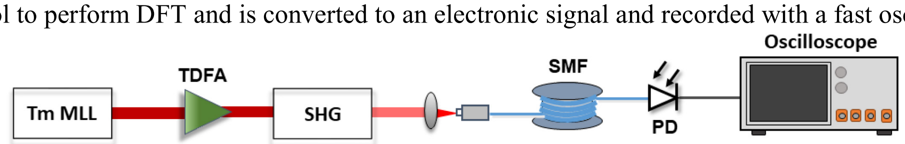

Fig. 1 Schematic of SHG-DFT setup for real-time dynamics analysis.

The laser operates in a single pulse mode-locking state for a coupled pump power of 197 mW. Before entering a double-pulsing regime with a pump power of 216 mW, the laser leaves its stable single pulsing operation and enters a regime where multiple operation states can exist depending on the polarization settings (PC) in the laser cavity for a pump power of 210 mW. For a particular PC setting, a chaotic state, where the pulses experience a semi-periodic evolution around 2,500 cavity roundtrips, is obtained and studied. For the presented laser parameters, the laser pulses do not converge to a particular solution, but rather, the pulses experience various phenomena in the complex solution space, and starting and ending in the same quasi-stable state. A selected evolution with a soliton explosion in the chaotic state is shown in Fig. 2(a). The evolution starts in a transient pulsing stage, then a sharp increase in intensity occurs around the 370th roundtrip, followed by an explosion, as revealed by the suddenly appearing broad spectrum. Weak interference fringes are observed after the explosion, indicating the existence of a transient soliton molecule. The pulse amplitude decays afterwards and the pulse is restored after undergoing intensity modulations and a center wavelength shift, evident by the spatial drift until the ~2000th roundtrip. The autocorrelation function from the 200th roundtrip to the 500th roundtrip in Fig. 2(b) shows the collision process when one pulse gets close to the main pulse so that they collide around the 372th roundtrip. A pulse walk-off from the main pulse occurs after the collision until it disappears eventually. The energy evolution, cf. Fig. 2(c), is separated into even (red) and odd (blue) roundtrips. The energy of the pulses from even and odd roundtrips is fairly constant until the ~350th roundtrip, then an abrupt energy jump is observed at the 372th roundtrip, corresponding to the explosion. Followed by a decreasing oscillatory behavior, the pulse energy envelope oscillates out of phase with every other roundtrip so that the energy buildup and subsequent oscillation envelope alternates between odd and even roundtrips. At around the 1,500th roundtrip, the even roundtrip pulses decay while the odd roundtrip pulses complete the pulse restoration process with damped oscillations before re-entering a transient pulsing regime. These explosions do not occur fully periodically, since they are associated with perturbation induced gain fluctuations, revealing the stochastic nature of the explosions in this chaotic state.

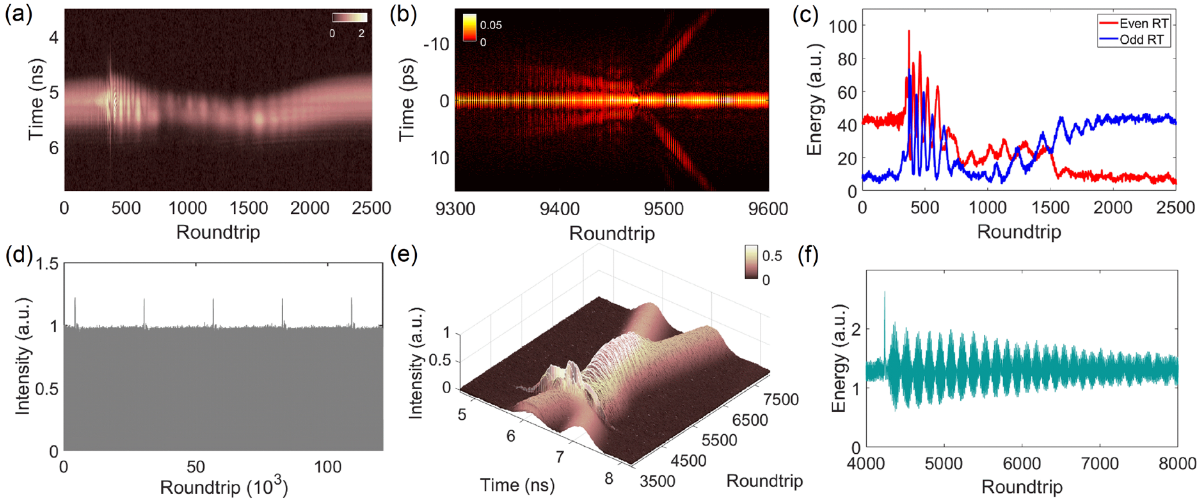

Fig. 2 Top row: Explosion dynamics in a transitionary chaotic state. (a) Spatial-spectral dynamics of the explosion. (b) Autocorrelation function with pulse collision and subsequent pulse walk-off. (c) Energy evolution of odd (blue) and even (red) roundtrips. Bottom row: Soliton collision induced explosions in a dual-wavelength mode-locking state. (d) Single-shot temporal recording of periodic collisions. (e) 3-D plot of a collision process with soliton trapping. (f) Energy evolution during collision period.

When increasing the pump power (to 248 mW), another interesting operating regime is obtained consisting of an orthogonal-polarized dual-wavelength vector soliton state. The corresponding 2 µm oscilloscope trace shown in Fig. 2(d) features periodic spikes of a value 1.2 beyond the normalized peak intensity of the pulse train. The spikes repeat roughly every ~27,910 cavity roundtrips, corresponding to a repetition frequency of ~2.8 kHz, which agrees well with the repetition rate difference between the two pulse trains, indicating that periodic collision events occur, similar to [3]. The 3-D plot in Fig. 2(e) shows the real-time collision process of two pulses. The two pulses propagate asynchronously at different group velocities until they eventually collide. At the moment of collision, a signature collapse associated with a wide spectrum of a soliton explosion is observed around the ~4,240th roundtrip. Before the pulses start to separate again and recover to their original state, they interact for ~2,500 cavity roundtrips. Dynamics during the interaction are further revealed in the pulse energy plot in Fig. 2(f). After the first energy spike which corresponds to the explosion, a damped energy oscillation is observed, indicating the nonlinear system is approaching an equilibrium state after the collision. Multi-period modulations are present during each damped energy oscillation, indicating that two additional modulations with different periods are fundamental to each modulation lob in Fig. 2(f). Without the presence of any polarization-maintaining components or spectral filters in the cavity, this polarization-multiplexed dual-wavelength state with slightly different repetition rates exhibits unique collision induced explosion dynamics. By studying the polarization projection of the two solitons here, a damped multi-period modulation confirms energy exchange between the polarization components due to coherent coupling, leading to a longer interaction time during the collision process.

In conclusion, we experimentally studied two types of soliton explosion dynamics in a linear Tm-doped mode-locked fiber laser for the first time. It is observed that multiple solutions, including soliton explosion, coexist in a chaotic state in the transition regime between a single and double pulsing state. Due to gain fluctuations these explosions occur stochastically. On the other hand, periodic explosions induced by soliton collisions are investigated in a dual-wavelength polarization multiplexed state. For our Tm-based laser system a prolonged soliton trapping process accompanied by a multi-period modulation is observed for the first time. These findings provide additional insights into Tm laser dynamics and potential laser design for stable and unstable operating regimes.

3. References

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