Noise-Like Dissipative Soliton Molecules in a Normal Dispersion Fiber Laser

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***Abstract*—We have developed a dissipative soliton fiber laser utilizing nonlinear polarization rotation mode locking. Through manipulation of the polarization controllers at a constant pump power, we have observed a transformation from the typical dissipative soliton molecules to the noise-like pulse dissipative soliton molecules.**

***Keywords*—dissipative soliton, fiber laser, noise-like pulse, soliton molecules**

I. Introduction

Passively mode-locked fiber lasers have garnered significant research attention due to their potential applications in fiber communications, material processing and all-optical sampling. They also serve as an ideal platform for exploring complex pulse dynamics and various nonlinear effects [1-3]. In particular, solitons generated in a normal dispersion mode-locked fiber laser, known as dissipative soliton (DS) can have significantly larger pulse energy. Consequently, fiber lasers operated in the normal dispersion regime have become a hot research topic [4–7]. In addition, by constructing a longitudinally non-uniform laser cavity with anomalous and normal dispersive fibers, the soliton can be periodically stretched and compressed during every roundtrip propagation, leading to partial pulse overlap [8]. This will enhance the interaction forces between pulses. Hereby, it is expected that the DS are susceptible to the formation of soliton molecules. Another pulse emission state commonly observed in fiber lasers is the noise-like pulse (NLP), which is a wave packet composed of many small pulses with random variations in peak power and pulse width. Compared to the DS, NLPs generated in the same fiber laser have much higher pulse energy. Most studies to date have focused on generating NLPs and soliton molecules in anomalous dispersion regime and normal regime [9]. However, there has been little research on NLPs in the normal dispersion region.

In this paper, we investigate the single soliton and soliton molecules of DS and NLPs in the same NPR-based mode locking fiber laser with net normal dispersion. The generation of single soliton and soliton molecules of DS and NLPs are determined by the pump power and intracavity birefringence, where a higher pump power can sustain the existence of multiple solitons. These results will give more sights on the characteristics of NLPs in fiber lasers with normal dispersion.

II. Experiment setup

The experimental setup of the fiber laser, as illustrated in Fig. 1, consists of a 1.2 m long erbium-doped fiber (EDF, Nufern SM-ESF-7/125) with a dispersion coefficient of -15.9 ps/nm/km providing sufficient gain for the laser. A 1.4 m long dispersion compensation fiber (DCF) with a dispersion coefficient of -131.3 ps/nm/km is utilized to manage the net dispersion of the fiber laser. Other fibers used are standard single-mode fiber (SMF) with a dispersion coefficient of 17 ps/nm/km. The total cavity length is 13.4 m and the net cavity dispersion is estimated to be~5.737ps^2 at 1555nm. nonlinear polarization rotation (NPR) mode-locking is achieved by using two polarization controllers (PC1, PC2) and a polarization-dependent isolator (PD-ISO). The cavity is pumped by a 980 nm laser diode (LD, Connet VLSS-980-B-600) through a 980/1550 wavelength-division multiplexer (WDM). An output coupler (OC) is placed after the DCF, where 20% of the intracavity field is output for data acquisition and analysis, while the remaining 80% continues to oscillate in the ring cavity. The output field is measured by an optical spectrum analyzer (OSA, Yokogawa AQ6370C) with a spectral resolution of 0.02 nm for an optical spectrum, a real-time oscilloscope (OSC, Keysight DSOS604A) with 6 GHz bandwidth for temporal waveforms, an electrical spectrum analyzer (ESA, Agilent N9320B) for radio frequency (RF) spectrum, and a commercial autocorrelator (Femtochrome FR-103XL) for pulse profile.

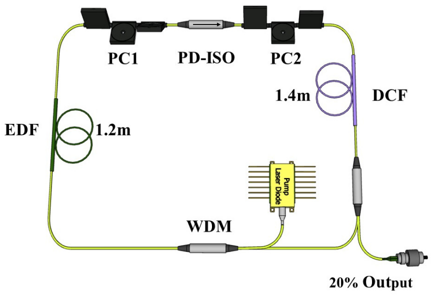

Fig. 1. Experimental setup of the normal dispersion fiber laser.

III. Experiment Results

A. Fundamental Mode-Locking and Noise-Like Pulse Operation

When the pump power is increased to 162 mW, a stable single soliton can be generated in the fiber laser, as depicted in Fig. 2. The laser generates a relatively broad DS spectrum as shown in Fig. 2 (a). Fig. 2(b) and (c) respectively show the oscilloscope trace and RF spectrum of the fundamental mode-locked DS. The pulse interval is 67 ns, which is consistent with the fundamental repetition rate of 14.9 MHz. The AC trace, displayed in Fig. 2(d). exhibits a Gaussian shape and the width of the single pulse is 6.4 ps. Fig. 2 (c) shows that the signal-to-noise ratio of the broadband spectrum exceeds 55 dBm, indicating the stability of the pulses generated by the laser.

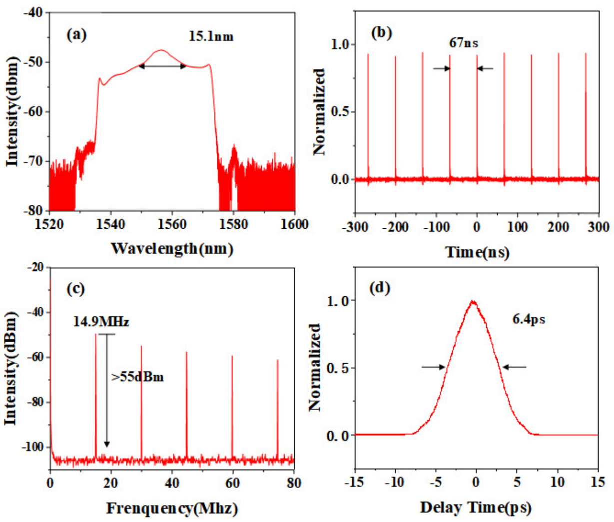

Fig. 2. Dissipative soliton operation. (a) Spectrum. (b) Oscilloscope trace. (c) RF spectrum. (d) AC trace.

Because the mode locking state is sensitive to the cavity parameter, the DS in a fiber laser can evolve into NLPs by adjusting the rotation angle of the intracavity PC. Once reaching the noise-like mode locking condition, redundant spectral components will show up in the optical spectrum, as shown in Fig. 3(a). The corresponding AC trace in Fig. 3(b) displays a typical feature of NLPs where a spike sitting atop a smooth pedestal. In the estimation of a Gaussian-shaped profile, the widths of the pedestal and the spike are 6.2 ps and 0.22 ps, respectively. The spike-to-pedestal intensity ratio is approximately 0.8, indicating that the sub-pulses within the NLPs have random variations in intensity.

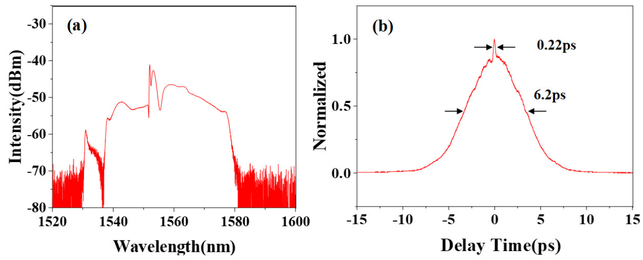

Fig. 3. Noise-like pulse operation. (a) Spectrum. (b) AC trace.

B. Conventional Dissipative Soliton Molecules and NLPs Soliton Molecules

By further increasing pump power and adjusting PCs, soliton molecule operation can be obtained at a pump power of 210 mW. Fig. 4 (a) illustrates the typical spectrum of the two-pulse soliton molecule, with a magnified view provided in the inset. The spectral modulation period is about 0.65 nm, corresponding to a pulse interval of 13 ps. The AC diagram in Fig. 4(b) displays three peaks with a peak-to-peak ratio of 1:2:1, suggesting that the two DS soliton peaks are equal. Moreover, the pulse interval is 2.8 times of the pulse width, indicating that two DS solitons are tightly bound together to form the pair. With proper tuning of the PC, we can observe the formation of double NLPs soliton molecules, whose spectrum and AC diagram are shown in Fig. 4(c)-(d), respectively. The spectral modulation period is about 0.38 nm corresponding to a pulse interval of 22.5 ps. The three peaks of the AC trace in Fig. 4 (d) consist of picosecond-level pedestals and femtosecond-level coherent spikes. The peak-to-peak ratio is no longer 1:2:1, and the peaks of the two NLPs solitons are unequal, possibly due to the random variation in the peak power and pulse width of many small pulses inside the NLPs.

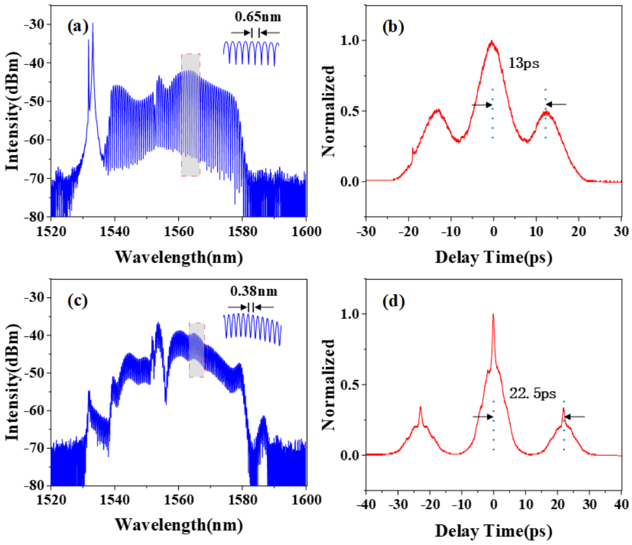

Fig. 4. DS and NLPs two-soliton molecules. (a) Spectrum and enlarged optical spectrum (b) AC for DS molecule. (c) Spectrum and enlarged optical spectrum (d) AC for NLPs molecule

Apart from the DS and NLPs pairs, this net-normal dispersion fiber laser can also produce multi-pulse DS and

NLPs molecules by increasing the pump power and accordingly adjusting the PCs status. Fig. 5(a) and 5(b) show three DS molecules, where the inset of Fig. 5(a) reveals the wavelength difference between the adjacent maximum peak and sub-maximum peak are both 0.27 nm. The AC trace in Fig. 5(b) indicates the pulse interval is 31.2 ps and the peak-to-peak ratio of 1:2:3:2:1 illustrates the three DS peaks are equal. By varying the PCs state at the same pump power, three-NLPs soliton molecules can be obtained. The modulation period of the spectrum shown in Fig. 5(c) is 0.75 nm corresponding to a pulse interval of 11.65 ps. The peak-to-peak ratio of 1:2:3:2:1 shown in Fig. 5(d) demonstrates that the three pulse peaks are the same.

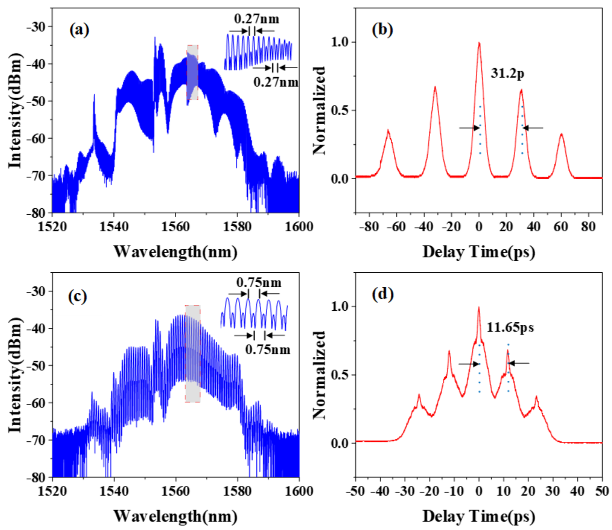

Fig. 5. DS and NLPs three-soliton molecules. (a) Spectrum and enlarged optical spectrum and (b) AC for DS molecule. (c) Spectrum and enlarged optical spectrum (d) AC for NLPs molecule

IV. CONCLUSION

In summary, we report a fiber laser which can sustain the generation of DS and NLPs in the normal dispersion regime. By varying the pump power and the intracavity birefringence, distinct nonlinear states including single soliton and soliton molecules of DS and NLPs are observed. These findings will improve our understanding of the relationship between DS and NLP.

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