Transient Dynamics of Generation and Annihilation in Multi-soliton Regime in a Mode-Locked Ring Laser

Junjie Zeng[1], Michelle Y. Sander[1, 2*]
[1]*Department of Electrical and Computer Engineering and BU Photonics Center, Boston University, Boston, MA 02215*
[2]*Division of Materials Science and Engineering, Boston University, Brookline, MA 02446*
*msander@bu.edu

Abstract: The transient dynamics of generation and annihilation between a double pulsing and three-pulse regime in a mode-locked fiber laser reveal significant fluctuations for the emerging pulse and spectral breathing behavior during the decaying process.

OCIS codes: (060.5530) Pulse propagation and temporal solitons; (140.4050) Mode-locked lasers; (320.7120) Ultrafast phenomena

1. Introduction

Dispersive Fourier transform (DFT) has enabled real-time measurements of both spectral and temporal information in ultrafast lasers for the first time to unveil the underlying dynamics of different ultrafast pulsation states. Various ultrafast pulse shaping mechanisms, including e.g. the mode-locking of a Ti:sapphire laser [1], multi pulse formation in a fiber laser [2] and transition from Q-switching to mode-locking [3] have been investigated with the technique. Here, we capture the temporal transition dynamics between consecutive multi-pulsing states, in particularly a double pulsing state and a three-pulse state.

2. Experimental Setup and Results

A single-walled carbon nanotube (SWCNT) based erbium-doped (Er) fiber ring laser is used to observe the transition between a double pulsing and a three-pulse state, as illustrated in Fig. 1. The laser consists of an 85 cm long Er gain fiber (Liekki Er80-8/125) and a saturable absorber based on SWCNT to operate in a soliton mode-locking regime with three additional polarization controllers. Unidirectional propagation within the cavity is ensured by incorporating an isolator. The fiber laser has a fundamental repetition rate of 44.1 MHz, corresponding to a round-trip time of 22.7 ns.

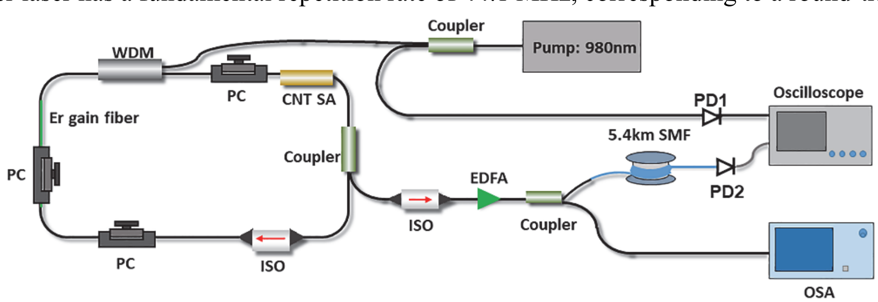

Fig. 1. Schematic of a CNT mode-locked Er fiber laser and the DFT setup to measure transition dynamics.

To analyze the transient dynamics of the multi-pulsing transition in the fiber laser, a DFT configuration is used. The pulse train is amplified in an Er-doped fiber amplifier and is stretched in a 5.4 km long SMF-28 fiber spool with a group delay dispersion of -117 ps^2 at the center wavelength. The stretched pulse train is coupled to a fast photodetector (EOT, 22 GHz), and connected to a real-time oscilloscope (Tektronix, 20 GHz). A small fraction of the pump light is split off to trigger the fast oscilloscope and to collect real-time analysis data of the generated pulses during the ramping up/down process of the pump power. As a result, a 20 ms continuous temporal trace of over 880,000 cavity roundtrips during each transition is recorded.

By adjusting the pump power, the laser operates in different multi-pulsing mode-locked states. Here, the transition dynamics from a double pulsing state to a three-pulse state are investigated. The optical spectra in Fig. 2(a) are similar in both states in steady-state, they are centered at a wavelength of 1567 nm with a full-width at half-maximum (FWHM) of 7 nm for the double pulsing state and 6.6 nm for the three-pulse state, which are induced by a coupled pump power of 66 mW and 78 mW. To study the generation process of the new pulse, the pump power is ramped up linearly over time between those two values. The corresponding evolution is revealed in the 2D contour map with over 15,000 roundtrips in Fig. 2(b). A background dispersive wave (DW) grows in between P1 and P3, which eventually leads to the formation of a new pulse. The 3D shot-to-shot evolution in Fig. 2(c), corresponding to the dashed box region in Fig. 2(b), provides more detail. The new pulse continues to grow significantly beyond the steady-state intensity value of 1, up to a value of 1.8. A beating between P1 and another background pulse evolved from a DW is noticeable, however, it dies out eventually due to gain competition.

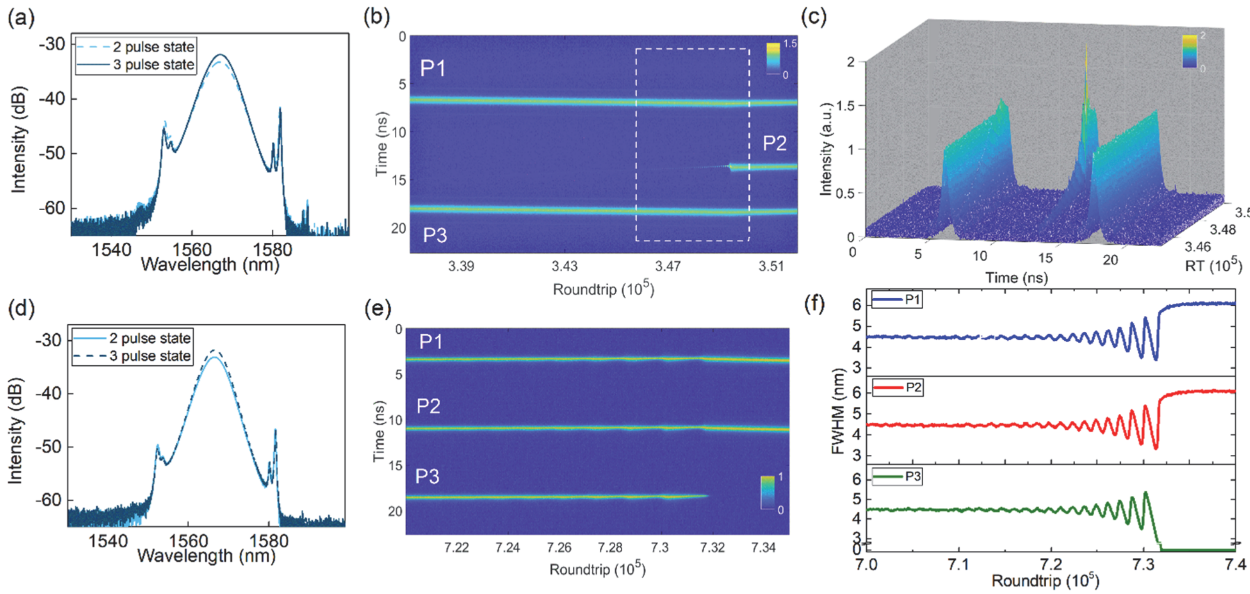

Figure 2. (a) Optical spectra in steady-state for a two and three pulse mode-locked state. (b) 2D contour plot during the soliton generation process when ramping up pump power. (c) 3D shot-to-shot temporal evolution of the dashed box in (b). (d) Optical spectra in steady-state before and after the pulse decaying transition. (e) 2D contour plot during the pulse annihilation process when the pump power is ramped down. (f) Retrieved spectral FWHM of the three individual pulses shows significant breathing behavior.

In addition, the reverse decay process with a pump power is decreased from 71 mW to 61 mW is examined. Fig. 2(d) displays the corresponding optical spectra in the steady state, where the FWHM changes from 5.9 nm for the three-pulse state to 6.2 nm for a double pulsing state. In Fig. 2(e), the contour map illustrates the temporal dynamics during the pulse annihilation process, and reveals a simultaneous breathing behavior among the three pulses until the pulse P3 disappears. The retrieved spectral FWHM is shown in Fig. 2(f), where all three pulses simultaneously undergo similar oscillations with a significant spectral breathing behavior. After one of the pulses decays, the FWHM of the remaining two pulses increases to 6.1 nm in steady-state.

The reported findings show that during the transition of generating a new pulse from a double-pulsing state, which gets initiated once the energy in the laser cavity exceeds a maximum soliton energy threshold, a new pulse formed through shaping of a narrow-band pulse arising from a DW. This differs from the pulse splitting processes that originate from a single pulse [4], while the original pulses remains stable. However, during the reverse transition from three-pulse state to doubling pulsing, a unique spectral breathing behavior is observed for the first time. The phenomenon can be associated with the gain and recovery dynamics and instability when the laser potentially reaches a bifurcation point, where three pulses are trying to survive but there is not enough gain to support all three pulses in the cavity, which is different from previously reported behavior [5].

In conclusion, we experimentally observed for the first time the transient growth and decaying of pulses in the multi-pulsing regime in a soliton mode-locked SWCNT-based Er-doped mode-locked fiber ring laser, utilizing the DFT technique. The additional new pulse is born from a background DW while the other two pulses maintain their shape and energy. The reverse decaying process reveals a unique breathing behavior which has not been reported before [6]. These findings offer important insights into the transition dynamics of multi-pulsing regimes for a passively mode-locked laser.

3. Acknowledgement

This work is supported by the National Science Foundation (ECCS-1710849).

4. References

[1] Herink, G., Jalali, B., Ropers, C., and Solli, D. R., *Nature Photonics*, 10(5), 321, (2016)
[2] Y. Yu, B. Li, X. Wei, Y. Xu, K. K. M. Tsia, and K. K. Y. Wong, *Applied Physics Letters*, 110(20), p. 201107, (2017)
[3] X. Liu, D. Popa, and N. Akhmediev, *Phys. Rev. Letters.*, 123, 093901 (2019)
[4] X. Liu and M. Pang, Laser & Photonics Reviews **13**, 1800333 (2019).
[5] G. Wang, G. Chen, W. Li, C. Zeng, and H. Yang, *Photonics Research*, 6(8), p. 825, (2018)
[6] J. Zeng and M.Y. Sander, Opt. Lett. 45, 5-8 (2020)