Observing the spectral dynamics of a mode-locked laser with ultrafast parametric spectro-temporal analyzer

Xiaoming Wei,[1] Chi Zhang,[2] Bowen Li,[1] and Kenneth K. Y. Wong[1,*]
[1]Department of Electrical and Electronic Engineering, The University of Hong Kong, Pokfulam Road, Hong Kong.
[2]Wuhan National Laboratory for Optoelectronics & School of Optical and Electronic Information, Huazhong University of Science and Technology, Wuhan 430074, China
**E-mail: kywong@eee.hku.hk*

Abstract: We experimentally observe the spectral dynamics of a passively mode-locked fiber laser by using a parametric spectro-temporal analyzer (PASTA) with a frame rate up to 100 MHz, and different non-repeating transient dynamics has been observed.

OCIS codes: (140.3510) Lasers, fiber; (320.7120) Ultrafast phenomena; (320.7150) Ultrafast spectroscopy

1. Introduction

Ultrashort pulse fiber laser based on passively mode-locking technique, featured with the compact design and reliable operation, has been strongly investigated and applied to various science fields, to name a few, the material processing, surgery, femtochemistry, bioimaging, metrology and optical communication [1]. The passively mode-locked cavity, on the other hand, is a versatile platform for studying ultrafast nonlinear dynamics, such as soliton molecules, pulsations, explosions and soliton rain [2]. The observation of those ultrafast dynamical processes in a mode-locked fiber laser, however, is still confined to the temporal domain by using high-speed photoreceivers [3,4]. While such kind of temporal characterization technique can only partially gain insight into transient dynamics, e.g. the self-starting mode-locking; the spectral dynamics of ultrafast events is largely unexplored owing to the lack of high-speed spectrum analyzer [5-8]. Techniques such as imaging grating spectrometer with beam scanner [5], gating photomultiplier tube (PMT) associated with monochrometer [6] and framing streak camera coupled with spectrograph [7], have been introduced to investigate the self-starting spectral transitions of a mode-locked laser [8]. These devices, unfortunately, have to be synchronized with the event to be observed, or operated in burst mode can only provide several frames per acquisition. Thus, it is unable to capture unique or even random spectral events inside a laser cavity. By using time-lens focusing mechanism, we recently demonstrated a real-time parametric spectro-temporal analyzer (PASTA), which enables a frame rate up to 100 MHz and accommodates various input conditions without synchronization requirements [9]. Here, we demonstrate the spectral observations of ultrafast dynamics of a mode-locked fiber laser by using PASTA.

2. Experimental setup and results

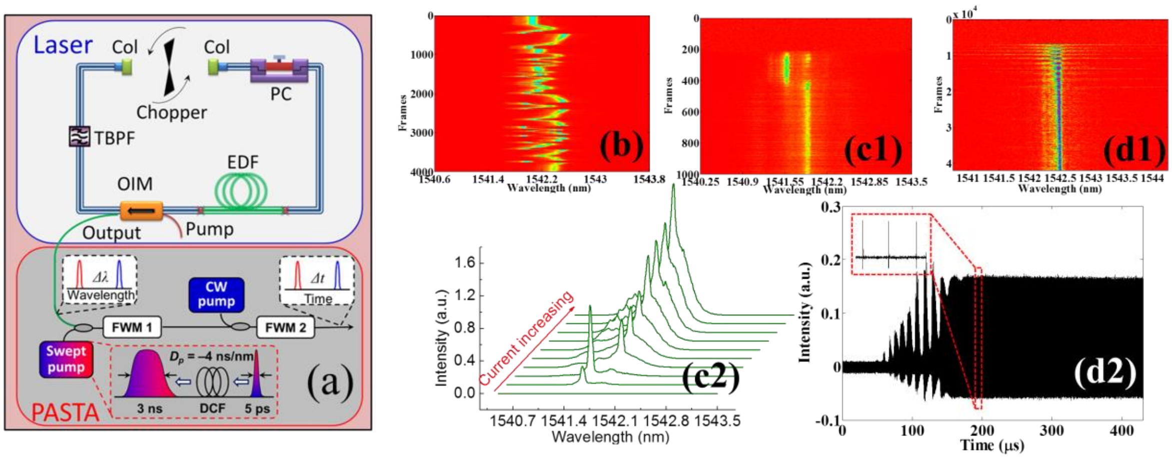

Fig. 1. (a) The experimental setup. (b) The spectral evolution of the mode-locked fiber laser measured by PASTA when PC was tuning. (c1) The spectral transient of the self-starting mode-locking measured by PASTA. (c2) The spectral transient of the self-starting mode-locking measured by optical spectrum analyzer, noted that the driving current was manually increased step by step in this case. (d1) The spectral transient of the mode-locked laser measured by PASTA when the chopper was opened. (d2) The corresponding temporal transient.

The mode-locked fiber laser monitored by PASTA is shown in Fig. 1(a), where the mode-locking was realized by the nonlinear polarization rotation (NPR) technique. A fiber-based optical integrated module (OIM) [10] with multi-functional, i.e. wavelength-division multiplexing, beam splitting and polarization-sensitive isolation, was used to construct the fiber ring. The state-of-polarization (SOP) of the lightwave was adjusted by an in-line polarization controller (PC, also served as the polarization scrambler). The gain medium was a piece of erbium-doped fiber (EDF, 0.6 m in length), and was pumped by a 980-nm laser diode (LD) through OIM. A mechanical chopper sandwiched by two collimators (Col) was introduced to control the operating conditions of the fiber laser. The lasing wavelength was selected by a 1-nm tunable bandpass filter (TBPF). To observe the spectral evolutions, the output of the mode-locked laser was launched into PASTA, which enables a variable frame rate of 0-100 MHz and a spectral resolution of 0.03 nm. In brief, PASTA was realized by two stages of four-wave mixing (FWM) involved in the time-lens implementation. The first stage FWM was a parametric mixer with chirped pump through a 4-ns/nm dispersive module. The second stage of FWM was employed to perform phase conjugation, which served as a spectral mirror. More details about the working principle of PASTA have been covered in Ref. 9.

First, we opened the chopper and randomly adjusted the SOP of the lightwave inside the cavity through polarization scrambling. The spectral behavior of the fiber laser is shown in Fig. 1(b). As can be observed, the wavelength of the fiber laser exhibited random variation, owing to the fact that the cavity loss is polarization-sensitive and thus the lasing wavelength would be determined by the SOP of the lightwave. Then, we measured the self-starting mode-locked dynamics of the fiber laser by PASTA when the driving current of the LD was suddenly increased from 0 to 200 mA. As shown in Fig. 1(c1), the fiber laser evolved from no emission to continuous-wave (CW) lasing, and ultimately mode-locking. The fiber laser was lasing at ~1541.5 nm at the beginning, and then switched to ~1541.9 nm where the mode-locking was achieved. To emulate this transient in a much slower process, we manually increased the driving current of the LD with a step of 20 mA, and recorded the optical spectrum of the fiber laser for each step with a conventional optical spectrum analyzer (OSA, YOKOGAWA AQ6370C), as shown in Fig. 1(c2). The stepping spectra (a slow process) matched with the PASTA measurement (a much faster process) quite well. Finally, we chopped the laser cavity, and captured the on/off transient of mode-locking by using PASTA at a frame rate of 100 MHz, as shown in Fig. 1(d). Different from the case shown in Fig. 1(c), the fiber laser directly evolved from Q-switched mode-locking to CW mode-locking, which was also identified by the temporal evolution measured with a 16-GHz real-time oscilloscope, as shown in Fig. 1(d2).

3. Conclusion

In conclusion, we have observed ultrafast spectral events of a mode-locked fiber laser by using a newly-designed high-speed spectro-temporal analyzer with a resolution of 0.03 nm and a frame rate of 100 MHz. It is believed that more unexplored and non-repeated events of the mode-locked fiber laser can be observed by using such kind of spectral analyzer with ultrahigh throughput.

4. Acknowledgment

This work was partially supported by grant from the Research Grants Council of the Hong Kong Special Administrative Region, China (Project No. HKU 17208414 and HKU 7172/12E) and University Development Fund of HKU.

5. References

[1] M. E. Ferma, A. Galvanauskas, and G. Sucha, Ultrafast Lasers: Technology and Applications (CRC, 2002).

[2] P. Grelu and N. Akhmediev, “Dissipative solitons for mode-locked lasers,” Nat. Photonics **6**, 84-92 (2012).

[3] J. Goodberlet, J. Wang, J. G. Fujimoto, and P. A. Schulz, “Starting dynamics of additive pulse mode locking in the Ti:Al2O3laser,” Opt. Lett. **15**, 1300 (1990).

[4] H. Li, D. G. Ouzounov, and F. W. Wise, ”Starting dynamics of dissipative-soliton fiber laser,” Opt. Lett. **35**, 2403-2405 (2010).

[5] Ł Zinkiewicz, F Ozimek, and P Wasylczyk, “Witnessing the pulse birth—transient dynamics in a passively mode-locked femtosecond laser,” Laser Phys. Lett. **10**, 125003 (2013).

[6] J. Kuo and C. Pan, “Buildup of steady-state subpicosecond and femtosecond pulses in a colliding-pulse mode-locked ring dye laser,” Opt. Lett. **15**, 1297 (1990).

[7] N. Sarukura and Y. Ishida, “Pulse evolution dynamics of a femtosecond passively mode-locked Ti:sapphire laser,” Opt. Lett. **17**, 61 (1992).

[8] D. Abraham, R. Nagar, V. Mikhelahsvili, and G. Eisenstein, “Transient dynamics in a selfstarting passively modelocked fiberbased soliton laser,” Appl. Phys. Lett. **63**, 2857 (1993).

[9] C. Zhang, J. Xu, P. C. Chui, and K. K. Y. Wong, “Parametric Spectro-Temporal Analyzer (PASTA) for real-time optical spectrum observation,” Sci. Rep.**3**, 2064 (2013).

[10] X. Wei, J. Xu, Y. Xu, L. Yu, J. Xu, B. Li, A. K. S. Lau, X. Wang, C. Zhang, K. K. Tsia, and K. K. Y. Wong, ”Breathing laser as an inertia-free swept source for high-quality ultrafast optical bioimaging,” Opt. Lett. **39**, 6593-6596 (2014).