2022 International Symposium on Nonlinear Theory and Its Applications, NOLTA2022, Virtual, December 12-15, 2022

Ultra-long-distance synchronization of DFB lasers induced by common digital-phase modulation CW light

Anbang Wang [1,2,3,4,*], Xiaohui Peng [1,2], Lin Jiang [5], Lianshan Yan [5], Yuncai Wang [3,4]

[1]Key Lab of Advanced Transducers and Intelligent Control System, Ministry of Education, Taiyuan, China
[2] College of Physics and Optoelectronics, Taiyuan University of Technology, Taiyuan, China
[3] School of Information Engineering, Guangdong University of Technology, Guangzhou, China
[4]Guangdong Provincial Key Laboratory of Photonics Information Technology, Guangzhou, China
[5]Center for Information Photonics and Communications, School of Information Science and Technology, Southwest Jiaotong University, Chengdu, China
Email: wanganbang@tyut.edu.cm

Abstract–Optical chaos-based key distribution encounters a problem in long-haul transmission which is limited by the distance of chaos synchronization. We propose and experimentally demonstrate a scheme of ultra-long-distance chaos synchronization of DFB lasers injected by a common digital-phase modulation CW light. Results show that high-quality synchronization can be achieved even when error bits exist between the driving signals. By utilizing long-distance optical coherent transmission of the digital signal, chaos synchronization over 8000-km single-mode fiber link is achieved.

1. Introduction

Physical key distribution with optical chaos synchronization in semiconductor lasers has shown great potential in securing data transmission of modern communication networks [1]. Porte *et al*. demonstrated a back-to back key distribution at 11Mb/s using synchronous chaos of mutually coupled semiconductor lasers to mask and exchange keys [2]. Yoshimura *et al*. proposed another key distribution using common-signal-induced chaos synchronization with phase-shift keying [3], and achieved 182-kb/s distribution rate over 120-km fiber transmission in photonic-integrated semiconductor lasers [4]. Recently, we proposed a 0.75-Gb/s key distribution over 160-km fiber with mode-shift keying chaos synchronization of Fabry–Perot lasers commonly driven by a super-luminescent diode [5]. Although the rate of chaos key distribution has made a great progress, the distribution distance is still around 100km. It can meet the transmission distance of metropolitan network but is far below that of interurban network or even backbone network beyond 1000-km fiber link.

ORCID iDs First Author: 0000-0001-5972-9566, Second Author: 0000-0002-4362-0723, Third Author: 0000-0001-8282-1176, Fourth Author: 0000-0002-3633-7161, Fifth Author: 0000-0003-2319-8913.

It is known that the distance of chaos synchronization determines that of key distribution. To achieve chaos synchronization, one needs to transmit the analog optical signal with large bandwidth over the fiber link. The fiber link involves many impairments such as chromatic dispersion, nonlinearity, and amplified spontaneous emission (ASE) noise which greatly distort the analog signal and thus degrade the synchronization distance [6]. In the reported synchronization methods, one usually adopts dispersion compensation fiber to mitigate the chromatic dispersion and ignores the other two influences. As a result, chaos synchronization over a fiber not exceeding 200km can be only established, as previously mentioned. Recent numerical reports and our excremental results show that the chaos synchronization can be extended to an extreme distance of about 1000km by further suppressing the impairments of nonlinearity and ASE noise, with digital-domain and optical-domain compensation methods, respectively [7,8]. However, lengthening the synchronization distance beyond 1000km with aforementioned methods becomes difficult because the fiber channel impairments to the analog signal cannot be compensated completely. It is therefore an ongoing challenge to develop methods of ultra-long-distance chaos synchronization for constructing the long-haul key distribution.

In this paper, we propose a scheme of ultra-long-distance synchronization using two distributed feedback (DFB) semiconductor lasers commonly driven by a continuous-wave (CW) light with digital-phase modulation. The digital signal can be shaped and regenerated perfectly with coherent transmission over the long-distance fiber, and resists the channel impairments better than the analog signal, thus affording a longer-distance chaos synchronization. Experimental results show that high-quality chaos synchronization over 8000-km fiber can be successfully achieved with the proposed scheme.

2. Experimental setup

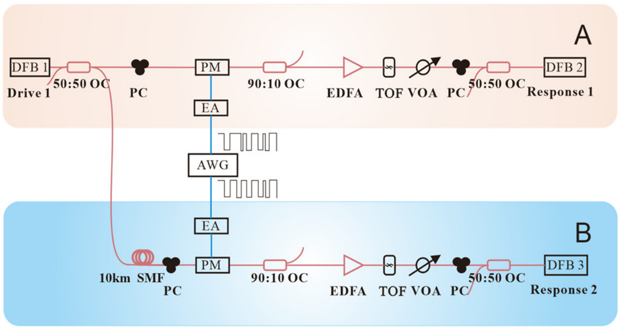

Fig. 1. Experimental setup. DFB Laser: Distributed feedback semiconductor laser; AWG: arbitrary waveform generator; SMF: single-mode fiber; EDFA: erbium-doped fiber amplifier; EA: electric amplifier; PM: phase modulator; PC: polarization controller; OC: optical coupler; TOF: tunable optical filter; VOA: variable optical attenuator.

Figure 1 shows the experimental setup of back-to-back chaos synchronization induced by common digital-phase modulation CW light. An arbitrary waveform generator is used to generate two similar digital signals. The digital signals are then amplified via electric amplifiers and are modulated on the CW light of DFB1 through the phase modulators. One of the modulated CW light is injected to DFB2 after optical amplification by erbium doped fiber amplifier and ASE suppression by tunable optical filter, and the other one to the DFB3, inducing the chaos synchronization.

3. Experimental results

Figure 2 shows the chaos synchronization between DFB1(R1) and DFB2 (R2) commonly driven by the CW light with a 16-Gb/s NRZ signal modulation. As presented in Figs. 2(a), the R1 and R2 have almost identical temporal waveforms. The scatter plot of the two chaotic waveforms concentrates around a straight line, as plotted in Fig. 2(d), which indicates a high-quality chaos synchronization. By quantitatively calculating the cross correlation, the synchronization is evaluated as high as 0.95.

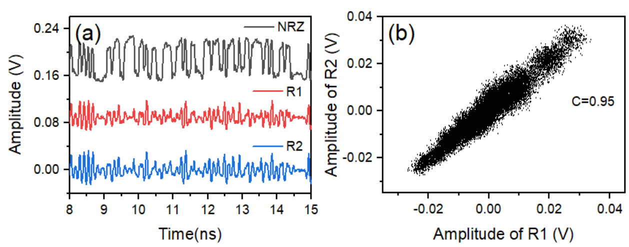

Fig. 2. Results of chaos synchronization: (a) Temporal waveforms of NRZ, R1 and R2; (b) Scatter plot of R1 and R2.

Having demonstrated the feasibly of NRZ signal-induced chaos synchronization, attention is turned to examining its potential of long-distance transmission. Note that, error bits are inevitably introduced to the digital signal duo to the long-distance fiber channel impairments. It is therefore necessary to investigate the influence of error bit rate (BER) on the chaos synchronization. Figure 3 shows the synchronization evolution as a function of the BER of NRZ signal. For a BER of 0.001, as shown by the inset (a), a high-quality chaos synchronization with a cross-correlation value of 0.95 can be achieved. With increasing the BER, the cross-correlation values degrade gradually to about 0.90 and 0.73, as shown by the insets (b) and (c), which correspond BERs of 0.020 and 0.100, respectively. It can be verified that high-quality chaos synchronization with a correlation value beyond 0.90 can be always established as long as the BER is not larger than 0.020.

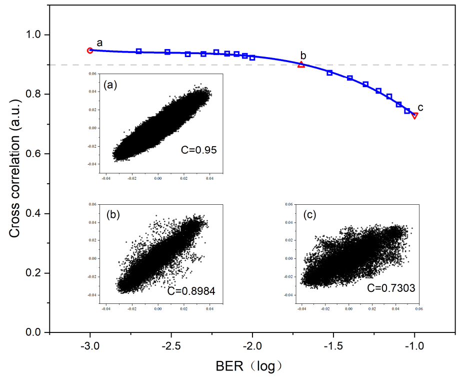

Fig. 3. Influence of bit error rate of NRZ signal on chaos synchronization.

Finally, we adopted a 32-Gb/s 16-ary quadrature amplitude modulation (QAM) signal to implement the experiment of long-distance chaos synchronization. The 16QAM signal after 8000-km fiber transmission is regenerated with a BER of 0.014 at the receiver end using coherent detection and digital signal processing algorithms. Commonly driven by the 16QAM signal after 8000-km transmission, a chaos synchronization with a correlation value of 0.91 is achieved experimentally, which will be presented detailly in our newly prepared paper.

4. Conclusion

A scheme of ultra-long-distance chao synchronization induced by common CW light with digital phase modulation is proposed and demonstrated experimentally. The feasibility of digital signal-induced chaos synchronization is firstly verified in a back-to-back scenario, and the maximum BER required for establishing the high-quality synchronization is identified as 0.020. With aforementioned investigations, an 8000-km chaos synchronization is established using a 16QAM signal. This scheme paves the way of long-distance key distribution based on chaos synchronization of semiconductor lasers.

Acknowledgments

This work was supported in part by National Key Research and Development Program of China (2019YFB1803500); NSFC (62035009, 61731014);

Shanxi “1331 Project” Key Innovative Team; Program for Guangdong Introducing Innovative and Enterpreneurial Teams; International Cooperation of Key R&D Program of Shanxi Province (201903D421012); Development Fund in Science and Technology of Shanxi Province (YDZJSX2021A009).

References

[1] A. Argyris, E. Pikasis, and D. Syvridis, “Gb/s one-time-pad data encryption with synchronized chaos-based true random bit generators,” *J. Lightwave Technol.* vol. 34, pp. 5325-5331, Nov. 2016.

[2] X. Porte, M. C. Soriano, D. Brunner, and I. Fischer, “Bidirectional private key exchange using delay-coupled semiconductor lasers.” *Opt. Lett.* vol. 41, pp. 2871-2874, 2016.

[3] K. Yoshimura, J. Muramatsu, P. Davis, T. Harayama, H. Okumura, S. Morikatsu, H. Aida, and A. Uchida, “Secure key distribution using correlated randomness in lasers driven by common random light,” *Phys. Rev. Lett*. vol. 108, Art. no. 070602, 2012.

[4] T. Sasaki, I. Kakesu, Y. Mitsui, D. Rotani, A. Uchida, S. Sunada, K. Yoshimura, and M. Inubushi, “Common-signal-induced synchronization in photonic integrated circuits and its application to secure key distribution,” *Opt. Express* vol. 25, pp. 26029-26044, 2017.

[5] H. Gao, A.B. Wang, L. S. Wang, Z. W. Jia, Y. Y. Guo, Z. S. Gao, L. S. Yan, Y. W. Qin, and Y. C. Wang, “0.75 Gbit/s high-speed classical key distribution with mode-shift keying chaos synchronization of Fabry–Perot lasers,” *Light: Sci. Appl. Vol.* 10, pp. 1-9, 2021.

[6] J. G. Wu, Z. M. Wu, Y. R. Liu, L. Fan, X. Tang, and G. Q. Xia, “Simulation of bidirectional long-distance chaos communication performance in a novel fiber-optic chaos synchronization system,” *J. Lightwave. Technol.* vol. 31, pp. 461–467, 2013.

[7] Z. Yang, L. L. Yi, J. X. Ke, Q. B. Zhuge, Y. P. Yang, and W. S. Hu, “Chaotic optical communication over 1000 km transmission by coherent detection,” *J. Lightwave. Technol.* vol. 38, pp. 4648 - 4655, 2020.

[8] Y. D. Fu, M. F. Cheng, W. D. Shao, H. W. Luo, D. Li, L. Deng, Q. Yang, and D. M. Liu, “Analog-digital hybrid chaos-based long-haul coherent optical secure communication,” *Opt. Lett.* vol. 46, pp. 1506-1509, 2021.