86-Gb/s Optical Chaos Communication over 100-km Fiber Transmission Using Semiconductor Lasers

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Abstract *An optical-chaos secure communication of 86-Gb/s 16-ary QAM signal over 100-km fiber transmission is experimentally demonstrated under the 20%-overhead SD-FEC BER threshold of 2.0×10^{-2} by using wideband chaos synchronization of discrete-mode semiconductor lasers.*

Introduction

With the ever-growing communication capacity, high-speed secure communications become increasingly important. Quantum cryptography provides secure keys but still has practical challenges such as low rate of key generation [1]. Optical chaos communication (OCC) is a promising alternative thanks to advantages in transmission rate and distance, and compatibility with mature fiber-optic communication system. The milestone filed experiment achieved in Athens metropolitan area network realized 1 Gb/s secure transmission over a 120-km fiber link [2].

Semiconductor lasers are popular chaos transceivers of OCC because of their high-complex waveforms and easy-to-integrate structure. European Union's framework programme PICASSO was launched and had taken the lead in developing the photonic integrated chaotic laser for communication [3, 4]. The main experimental developments of rate and distance of OCC using semiconductor lasers are summarized in Fig. 1. The OCC rate is limited below 10 Gb/s for DFB, VCSEL, and FP lasers with direct chaos masking. Complicated bandwidth-enhancement methods such as mutual-injection have a challenge in long-distance communication [5]. Recently, chaotic phase scrambling methods have been demonstrated to realize 28 Gb/s over 100 km fiber transmission [6]. Using chaotic opto-electric oscillators (OEOs) can achieve higher OCC rate; nevertheless, chaotic OEOs are difficult to be integrated because a high-gain wideband radio-frequency driver of modulator is required [7, 8]. Therefore, there is still a large rate gap between the semiconductor-laser based OCC and the traditional communication with rate of ~100 Gb/s.

In this paper, wideband chaos synchronization with a carrier bandwidth of 30 GHz is achieved using discrete-mode semiconductor lasers (DMLs). Then, 86-Gb/s secure communication over 100-km fiber transmission is demonstrated experimentally by chaos masking of 16-ary quadrature amplitude modulation (QAM) signal.

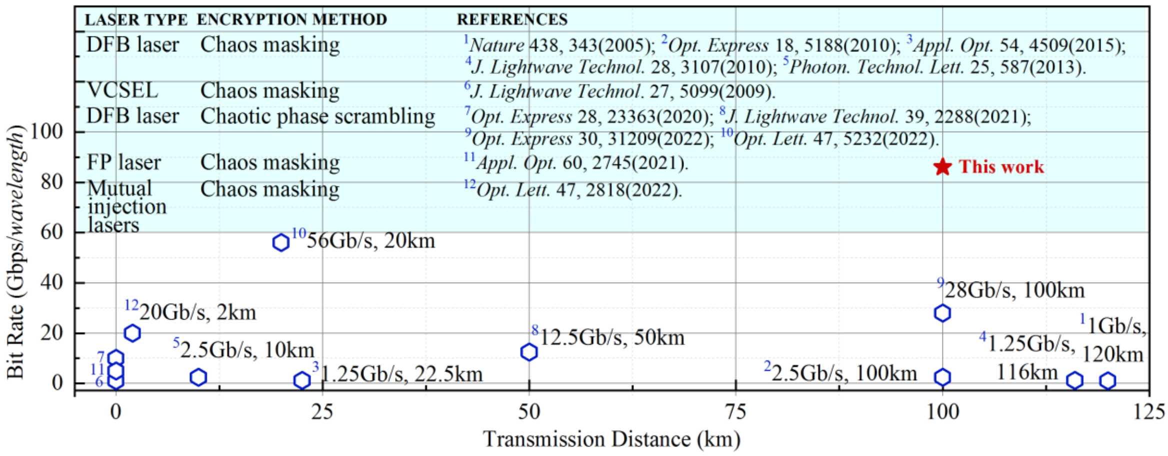

Fig. 1: Experimental developments of optical chaos communication using semiconductor lasers.

Experimental Setup and Method

Figure 2 shows the experimental setup. The transmitter and the receiver are parameter-matched DMLs (Eblana EP1550-0-DM-B05). The drive is a DML with dispersive optical feedback from a chirped fiber Bragg grating (CFBG), shown in the dashed box, to generate a wideband chaos without time signature [9]. The drive light $E_D(t)$ is injected into the transmitter to generate a chaotic light with intensity $C(t)$. After opto-electrical conversion by a 50-GHz photodetector (FINSAR XPDV2120RA), $C(t)$ is mixed with a 16QAM signal $m(t)$ which is mapped from a binary data sequence to realize chaos masking. The mixed signal $I_S(t) = C(t) + m(t)$ is converted into an optical signal by modulating a continuous-wave light at a wavelength λ_S, and then is transmitted to the receiver end together with the drive light using wavelength division multiplexing. The fiber link has two spans, each consisting a 45-km single mode fiber, 5-km dispersion compensated fiber and an optical amplifier. The total length is 100 km.

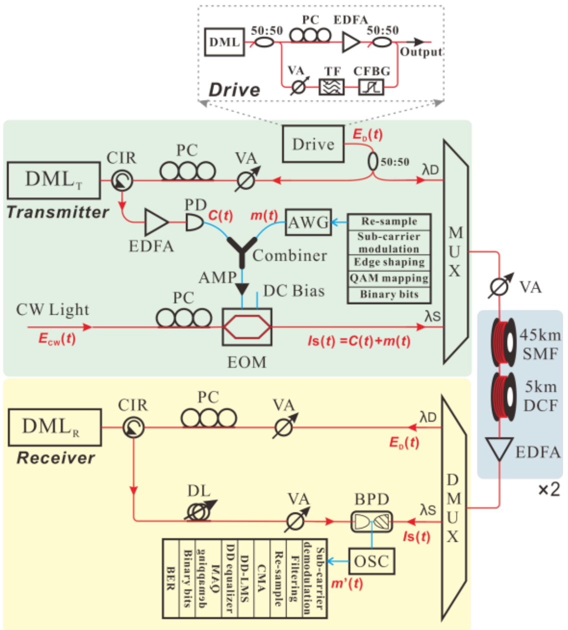

Fig. 2: Experimental setup. CIR, circulator; PC, polarization controller; VA, variable attenuator; EDFA, erbium-doped fiber amplifier; PD, photoelectric detector; AWG, arbitrary waveform generator; AMP, amplifier; EOM, electro-optical modulator; MUX, multiplexer; DML, discrete-mode laser; TF, tunable optical filter; CFBG, chirped fiber Bragg grating; SMF, single mode fiber; DCF, dispersion compensated fiber; DMUX, demultiplexer; BPD, balanced photodetector; DL, delay line; OSC, real-time oscilloscope.

In receiver end, after demultiplexing the drive light $E_D(t)$ is injected into the receiving laser to generate a chaotic light with intensity $C'(t)$. After adjusting injection power, delayed chaos synchronization $C(t) = C'(t)$ can be obtained. Thus, the masked signal can be decrypted by chaos cancellation $m'(t) = I_S(t) - C'(t)$ through a balanced photodetector (FINSAR BPDV2150R, bandwidth 45 GHz). Decrypted $m'(t)$ is recorded by a real-time oscilloscope (Tektronix DPO75902SX, bandwidth 59 GHz) and is processed with digital signal processing. In demonstration experiments, the transmitting and receiving lasers are biased at 44.882 mA (3.70 I_{th}) and 45.076 mA (3.73 I_{th}), respectively. Their solitary wavelengths are 1548.039 nm and 1548.031 nm, respectively, slightly lower than the drive light wavelength λ_D. In addition, we set λ_S = 1550.52 nm for WDM transmission with a channel width of 100 GHz.

Experimental Results and Analysis

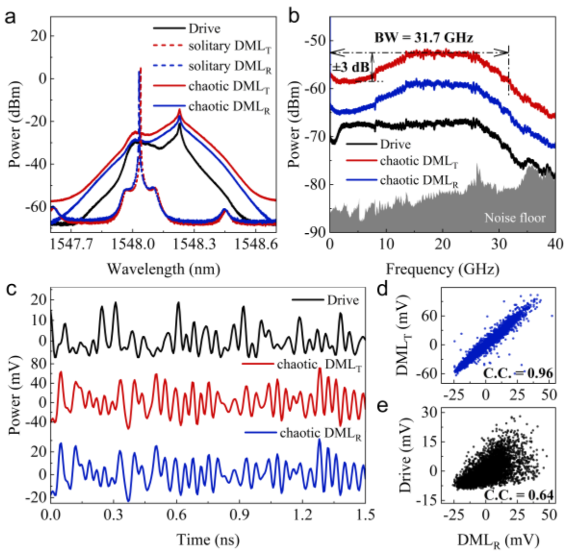

Fig. 3: Chaos synchronization results. a, optical spectra; b, radio-frequency spectra; c, temporal waveforms; d and e, scatterplots.

Figure 3 shows the results of wideband chaos synchronization in back-to-back (BtB) case. Shown in Fig. 3a, the optical spectra of DML$_T$ and DML$_R$ are broadened and their peaks are red-shifted to the spectral peak of drive light (1548.288 nm). In addition, near to the solitary wavelength, there is a side mode caused by the index pattern in DMLs. Thanks to the beating between the main mode and the side mode, the electrical spectrum of laser is extended greatly. As depicted in Fig. 3b, the two lasers have wide and flat electrical spectra (red and blue). The bandwidth can reach 31.7 GHz within ±3 dB power fluctuation. Further, the spectra of the lasers are highly similar but obviously different from the spectrum of drive light (black). This indicates that the transmitting and receiving lasers achieve wideband chaos synchronization, and have a low correlation with the drive light. This is proven by the time series in Fig. 3c and the corresponding scatterplots in Figs. 3d and 3e. The synchronization coefficient evaluated with correlation coefficient (C.C.) is calculated as 0.96, while the correlation between the drive light and the chaotic carrier is only 0.64. The low drive-carrier correlation ensures that one cannot use the drive signal to attack successfully, which will be shown subsequently.

Figure 4 demonstrates the results of message encryption and decryption of 16QAM signal after 100 km transmission, which was obtained by optimizing the launching power as 3.5 mW. Figure 4a plots the optical spectra of the encryption light (right) as well as the drive (left) before (black) and after (red) fiber transmission. The optical spectrum of DML_R is like that of BtB result. Due to the optical amplifier noise, the synchronization coefficient is reduced to 0.91. Figure 4b shows the constellation diagram of original 80-Gb/s 16QAM signal. Figures 4c and 4d plot constellation diagrams of encrypted and decrypted signals, and Fig. 4e shows the attack result using the drive light to decrypt. The corresponding bit-error ratios (BER) are 1.3×10^{-1}, 1.7×10^{-2}, and 1.1×10^{-1}, respectively. Taking the 20%-overhead soft-decision forward error correction (SD-FEC) BER threshold of 2.0×10^{-2} as criterion, one can find the effective optical-chaos communication is achieved. Note that, these results are obtained under a low chaos masking coefficient $\rho = A_k/6\sigma_C$, where A_k and σ_C represent peak-to-peak value of k-order signal $m(t)$ and standard deviation of chaos carrier $C(t)$, respectively.

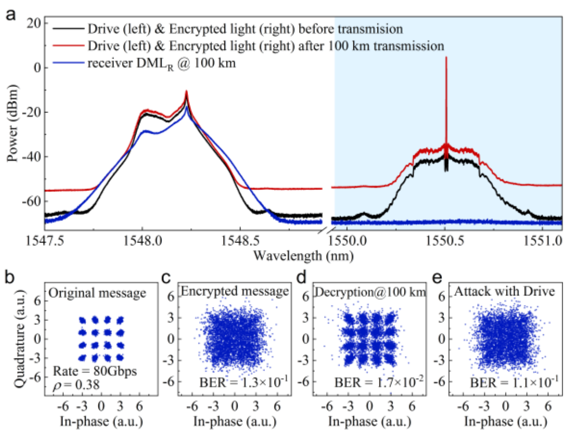

Fig. 4: Transmission and message decryption. a, optical spectra via wavelength division multiplexing; b-e, demonstrations of encryption and decryption of 80-Gb/s 16QAM message.

Figure 5a shows the influence of masking coefficient ρ on the decryption BER and attack BER. As increasing the masking coefficient, the BER of attack keeps beyond the SD-FEC threshold. By contrast, the BER of legal decryption decreases and becomes lower than the threshold at $\rho = 0.27$ for BtB and at $\rho = 0.35$ for 100-km transmission. That means effective masking for 100-km transmission requires $\rho > 0.35$. Figure 5b depicts the BER of legal decryption as a function of data rate at $\rho = 0.43$, which is the maximal masking coefficient available in our experiments. One can find that the BER increases as the data rate, and the maximal rates of 96 Gb/s and 86 Gb/s can be achieved in BtB and 100-km cases, respectively. According to Ref. [10], applying artificial neural networks can decrease the BER to SD-FEC threshold when the raw data BER is less than 8.0×10^{-2}. Thus, our system has a promising potential to achieve 100-Gb/s secure data transmission over 100 km, because its raw BER is 3.7×10^{-2}.

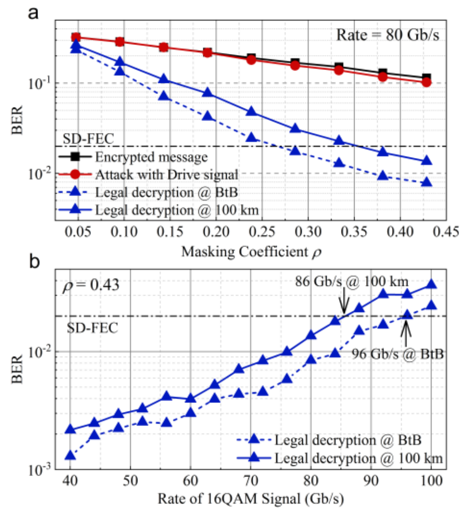

Fig. 5: a, BER versus masking coefficient ρ; b, decryption BER (at $\rho = 0.43$) versus the 16QAM signal rate.

Conclusions

Optical chaos communication with 86 Gb/s 16QAM signal over 100-km fiber transmission is experimentally achieved, benefiting from wideband chaos synchronization of discrete-mode lasers subject to common drive. It is promising that the transmission rate can be enhanced to 100 Gb/s using artificial neural networks. We hope that this method can open an avenue of optical secure communication for high-speed metropolitan area network.

Acknowledgements

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