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REVIEW ARTICLE

Key technologies in chaotic optical communications

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Abstract In this paper, the key technologies and research progress of chaotic optical communication are reviewed. We first discuss the chaos generation methods based on different nonlinear components. Then we focus on the frontiers of chaotic optical communications, including how to improve the security, and the development about the transmission capacity and distance of chaotic optical communication in laboratory and field. At last, we discuss limitations and potentials of chaotic optical communications and draw a conclusion.

Keywords chaos, chaotic optical communications, security, capacity, time delay concealment

1 Introduction

The laser was invented in 1960 by Maiman [1], and the concept of chaos was proposed in 1963 by Lorenz [2]. However, since then, chaos and lasers were developed individually for a long time. Until 1975, the connection between chaos and lasers was first established by Haken [3]. After that, many experiments about observation of chaotic laser dynamics were studied, and many proposals of laser models were used to explain the experiment results. In 1990, control and synchronization of chaos were firstly proposed [4], which broadened the applications of chaos, such as chaotic optical communications, random number generation and secure key distribution. Chaos systems are highly sensitive to the initial conditions, which make them hard to be predicted and have potential of providing high level privacy in data transmission. So chaotic optical communications have attracted a lot of attentions for realizing information secure in physical layer. And many experiments on chaos-based optical communications have been demonstrated. The techniques of generating the chaos can be classified based on the nonlinear dynamics of different optical components, including all-optical feedback and optoelectronic feedback based on nonlinear dynamics in semiconductor lasers, electro-optic feedback based on nonlinear dynamics in Mach-Zehnder electro-optic modulator and so on. Among them, electro-optic feedback is more likely to be used in high-speed chaotic optical communications due to the high bandwidth of electro-optic components.

A field experiment of chaotic laser-based secure optical communications on commercial optical networks was firstly demonstrated in 2005, where transmission rates in gigabit per second and corresponding bit-error rates below 10^{-7} after decryption were achieved over 120 km fiber transmission, which shows the feasibility of chaotic lasers for long-distance, high-speed secure optical communication systems [5]. Since then, researchers have focused on improving the transmission speed, synchronization quality and security level of chaotic optical communications. In 2010, transmission rates at 10 Gb/s with more than 100 km transmission distance have been achieved [6] with enhanced security using phase chaos generated by phase modulator (PM). However, researchers found that most schemes of chaotic optical communication were not as secure as expected [7]. Many schemes such as autocorrelation functions, mutual information and extrema statistics can be used to get the feedback time delay, which is a critical secure key in chaotic systems [8–11]. Once eavesdroppers get the time delay, all other hardware parameters can be estimated. Therefore, completely concealing the time delay is important to enhance the security of chaotic optical communications. Many methods have been proposed to conceal the time delay. For example, choosing the feedback delay time around the relaxation frequency of the lasers can be used for concealing the time delay [12], but at the expense of reducing the chaotic complexity. Therefore, a valid time delay concealment method is required. On the other hand, increasing the complexity of chaotic systems is another way to improve the security. After solving the security issues, increasing the transmission capacity and distance of chaotic optical communications becomes more important

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for practical applications. The contents of this paper are organized as below: we first introduce different chaos generation methods, which are classified based on the nonlinear dynamics of different optical components, then we provide an insight review on the key technologies of enhancing the security, including concealing the time delay and increasing the chaotic complexity. The laboratory and field demonstrations of high speed chaotic optical communications are then introduced. At last, we discuss the limitations and perspectives of chaotic optical communications and draw a conclusion.

2 Components for chaos dynamic generation

Generation of chaotic signals is an important part in chaotic optical communications. Generators of chaos can be classified based on the nonlinear dynamics originated from different components, including semiconductor lasers, Mach-Zehnder modulator (MZM) and Mach-Zehnder interferometer and so on.

2.1 Semiconductor lasers

Figure 1 shows the three ways to generate chaos from the nonlinear dynamics of semiconductor lasers, including all optical feedback, optical injection and optoelectronic feedback configurations [13]. All optical feedback is the most fundamental configuration to generate chaos. As shown in Fig. 1(a), the light from the lasers is reflected back to the laser cavity by an external mirror, which disturbs the interaction between the carrier and photon and induces chaos in semiconductor lasers. Figure 1(b) shows the schematic of chaos generation by optical injection, where the light from one lasers is injected into the other lasers, and an optical isolate is used for unidirectional injection. Chaos can be observed when the frequency of two lasers is detuned and the injection strength is small. Figure 1(c) shows the schematic of chaos generation by optoelectronic feedback, where a photodetector detects the light emitted from a semiconductor laser, and the photocurrent amplified by an amplifier is fed back to the injection current, which disturbs the carrier density and generates chaos.

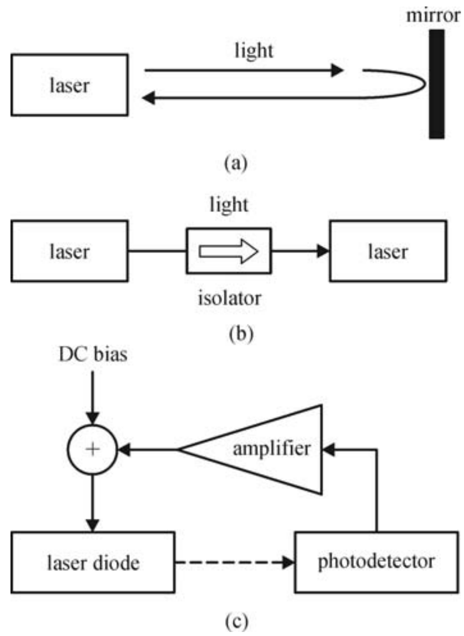

Fig. 1 Schematic of chaos generation induced by semiconductor lasers. (a) Optical feedback; (b) optical injection; (c) optoelectronic feedback (Ref. [13])

2.2 Mach-Zehnder modulator

In 2002, Goedgebuer et al. proposed a new chaotic system, where chaos is induced by the nonlinearity of MZM [14]. As shown in Fig. 2, the chaotic emitter consists of two laser diodes, and one of the laser diode outputs is modulated by a closed electro-optical feedback delay loop, where the nonlinear component is a high-speed lithium niobate MZM with low half-wave voltage (V_π), and the photodiode is used to convert optical signals into electrical signals, which

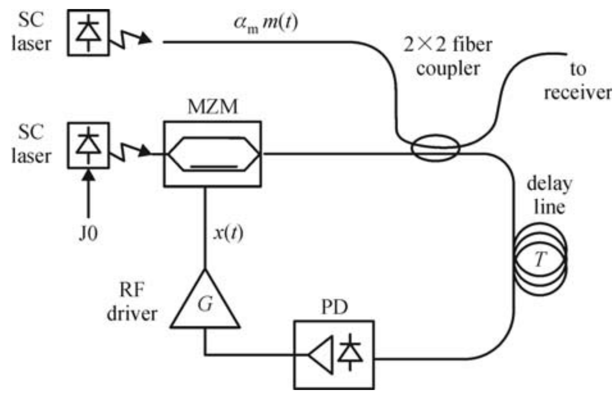

Fig. 2 Schematic of chaos induced by Mach-Zehnder modulator (MZM) (Ref. [15]). SC: semiconductor; MZM: Mach-Zehnder modulator; RF: radio frequency; PD: photodetector

is feedback to the modulator after being amplified. Once the amplitude of the converted electrical signal is more than two or three times of V_π, the chaos can be generated. The message carried by another semiconductor laser is mixed with the chaotic signal by a coupler [15]. Noted that the message participates in the chaotic generation process by perturbing the original chaotic dynamics, thus further increases the chaotic complexity. This method was supposed to support multi-10 Gbit/s chaotic optical communications attributed to the high bandwidth of commercially available MZM.

In order to increase chaos complexity, Nourine et al. proposed a new optoelectronic architecture based on the scheme of MZM [16]. As shown in Fig. 3, the nonlinearity originates from a wideband quadrature phase-shift-keying (QPSK) modulator. The two-dimensional nonlinearity and dual-delay feedback dynamics increase the chaos complexity and bandwidth. This scheme can generate chaos bandwidth from 30 kHz to 13 GHz.

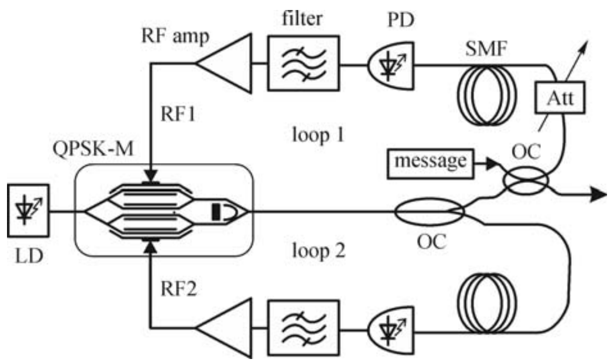

Fig. 3 Schematic of chaos induced by quadrature phase-shift-keying (QPSK) electro-optic modulator (Ref. [16]). LD: laser diode; QPSK-M: quatrature phase-shift-keying modulator; RF: radio frequency; amp: amplifier; SMF: single mode fiber; Att: attenuator; OC: optical coupler; PD: photodiode

2.3 Mach-Zehnder interferometer

Optical phase chaos system was proposed in 2009 by Lavrov et al. [17] with the objective of increasing the crack difficulty since the phase chaos is with a constant amplitude. As shown in Fig. 4, the MZM in Fig. 2 is replaced by a high speed PM. An imbalanced Mach-Zehnder interferometer is used to convert the phase into intensity for generating the driven signal of the PM. In this system, the nonlinearity is originated from the Mach-Zehnder interferometer rather than the PM. This kind of system has realized 10 Gb/s chaotic optical transmission in an installed optic network by Lavrov et al. in 2010 [6], which is the record transmission speed in field demonstration of chaotic optical communications by far.

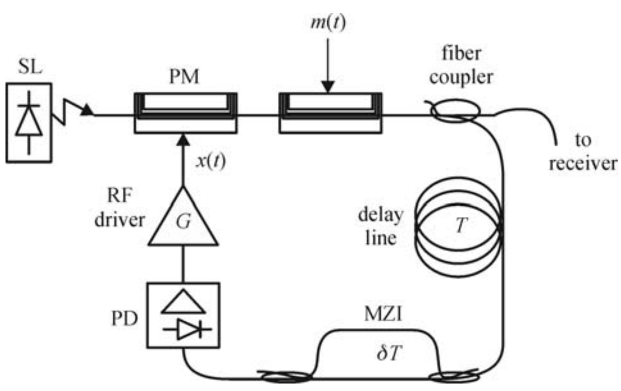

Fig. 4 Phase chaos emitter setup (Ref. [13]). SL: semiconductor laser; PM: phase modulator; RF: radio frequency; PD: photodiode; MZI: Mach-Zehnder interferometer

3 Frontiers of chaotic optical communications

Since field demonstration about chaotic optical communications was first demonstrated in 2005 [5], research topics have been focused on how to improve the transmission speed and chaotic synchronization quality. Meanwhile, people have found chaotic optical communications are not secure as expected [8–11], therefore chaotic security becomes more and more important. Once the security issue is solved, increasing the transmission capacity and distance of chaotic optical communications becomes more important for practical applications. So research frontiers of chaotic optical communications are mainly about how to improve the security and how to improve the transmission capacity and distance of chaotic optical communications.

3.1 Security enhancement

3.1.1 Time delay concealment

Researchers have found that many methods such as autocorrelation functions, mutual information and extrema statistics can be used to get the time delay signature (TDS) [9], in addition, the power spectrum analysis method can also be used to get the TDS [8]. The delay time is a critical parameter, according to the delay time, other hardware parameters can be easily estimated. So the possibility of identifying the TDS becomes a severe problem in chaotic optical communications. In order to improve the security of chaotic optical communications, concealing the time delay is indispensable. Since the time delay concealment methods in all-optical and electro-optic feedback chaotic systems are different, thereby we respectively introduce the methods based on the two different configurations.

3.1.1.1 Time delay concealment in all-optical feedback chaotic systems

Various methods have been proposed to conceal the TDS. For example, if we choose the delay time close to the relaxation period of the lasers operating with moderate feedback, the TDS can be concealed [12]. As shown in Fig. 5, Figs. 5(a1) – 5(d1) and 5(a2) – 5(d2) respectively represent autocorrelation function and mutual information in different feedback rates, and the vertical dashed line indicates the TDS. The results show that the TDS can be concealed when the feedback rate is low and the value of delay time and relaxation period are close. However, it has been shown that the correlation between the phase and its delayed version in the dynamics can also be used to get the TDS [11]. In order to solve this problem, a more advanced method has been proposed, as shown in Fig. 6. In this scheme, because of the cross-feedback between the counter propagating modes in the bidirectional semiconductor ring

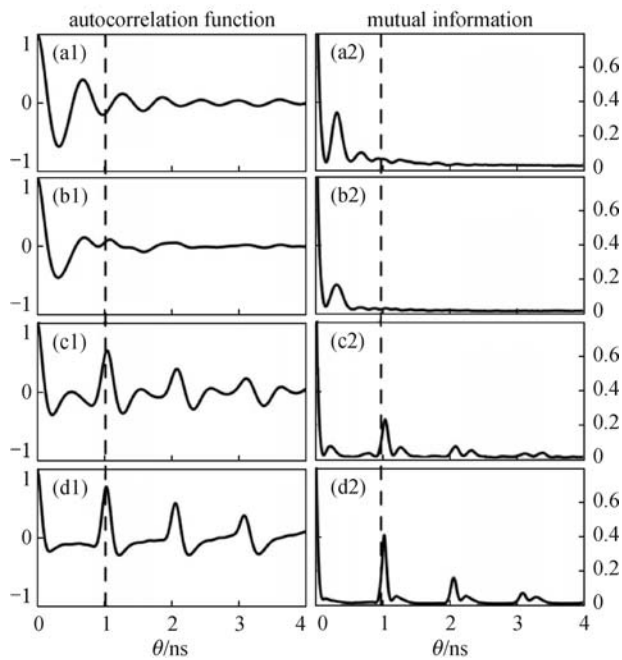

Fig. 5 Time delay concealment in autocorrelation function and mutual information (Ref. [12])

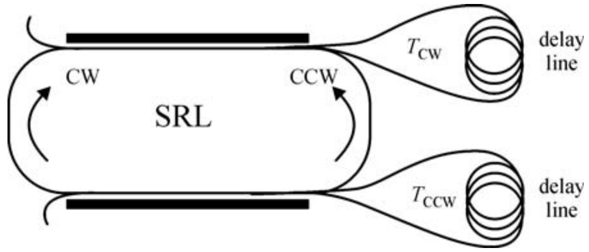

Fig. 6 Schematic of semiconductor ring lasers with cross-feedback (Ref. [18]). CW: clockwise mode; CCW: counter-clockwise mode; SRL: semiconductor ring lasers

lasers, the TDS both in intensity and phase can be eliminated [18].

In order to completely conceal the TDS, we also proposed a new architecture as show in Fig. 7, where a commercial tunable dispersion compensator (TDC) was introduced in the all-optical feedback loop [19]. Because of the present of the TDC module, different frequency components of the chaotic carrier experience different delay time, therefore the time periodicity is broken and the TDS is vanished. The results show that the TDS can be completely concealed from both time series and power spectrum analysis methods when the dispersion value is big enough as shown in Fig. 8. Noted that this methods is also feasible in electro-optic feedback chaotic systems.

3.1.1.2 Time delay concealment in electro-optic feedback chaotic systems

In order to conceal the time delay in electro-optic feedback

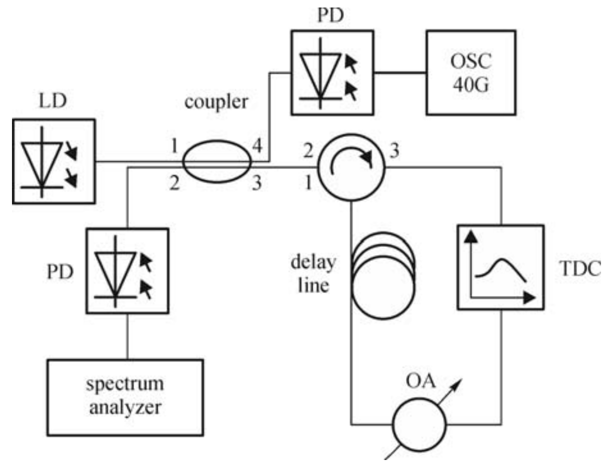

Fig. 7 A new scheme of time delay concealment [19]. LD: laser diode; PD: photodiode; OSC: oscilloscope; OA: optical attenuator; TDC: tunable dispersion compensator

chaotic systems, researchers have proposed a new architecture by combining, all-optical and electro-optic schemes as shown in Fig. 9, where all-optical intensity chaos and electro-optic phase-chaos systems are cascaded [20]. However, because the overall transmitted phase is a linear superposition of the all-optical and electro-optic systems, we can also use the correlation between the phase and its delayed version in the dynamics to retrieve the TDS [11].

Another new scheme has been proposed to radical conceal the TDS in electro-optic chaotic systems as shown in Fig. 10 [21]. In this scheme, a digital key was introduced into a phase-chaos electro-optic delay system, which contain two delay chains, and each chain has two electro-optic PMs. In each chain, the first PM is driven by an external signal which are the message and the digital key respectively, while the second PM is driven by the output of the other chain. In this scheme, the Mach-Zehnder interferometer transforms the phase variations into intensity variations in nonlinear way, and the intensity variations are detected by a photodiode then drive the PM after amplification for phase chaos generation. When the digital key is present and operate at a bit rate above a threshold given by the differential delay time of the chain in which the key is introduced, time-delay concealment can occur [21].

Based on the configuration of Fig. 10, an optimized system with two delay loops operating in parallel was proposed [22]. As shown in Fig. 11, there are two nonlinear delayed differential processing loops connected in parallel in both emitter and receiver. Only the output of one loop is transmitted to the receiver while the other loop remains internal. The configuration can conceal the internal time delays without an external digital key, which is different from the configuration in Ref. [21]. In fact, the dynamics of internal loop is uncorrelated to the

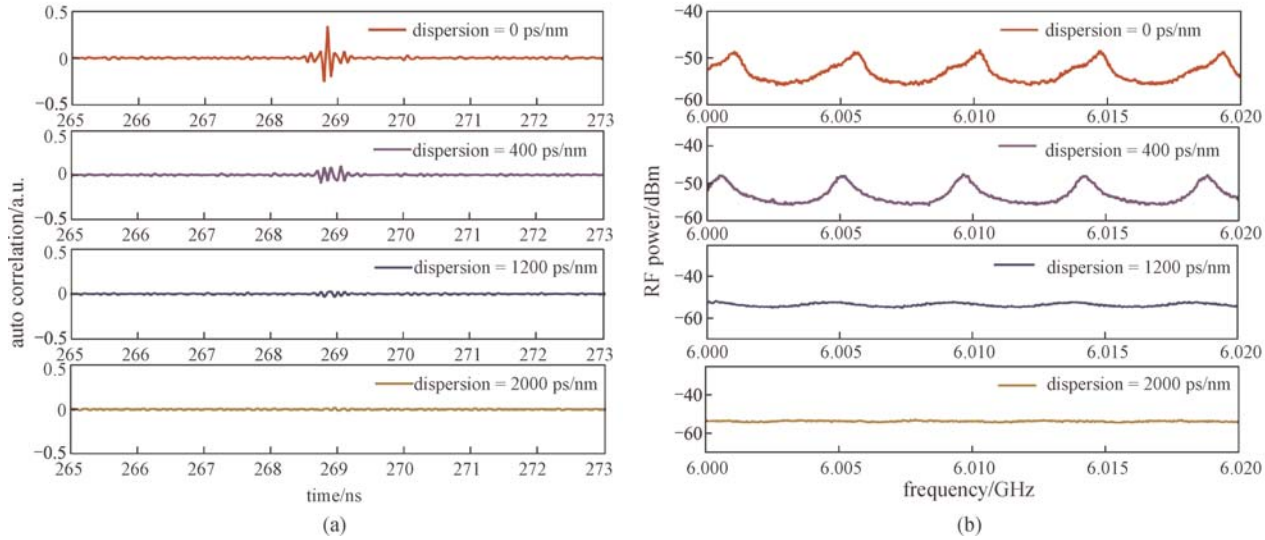

Fig. 8 Results of time delay concealment in auto correlation (a) and power spectrum (b) with different dispersion values (Ref. [19])

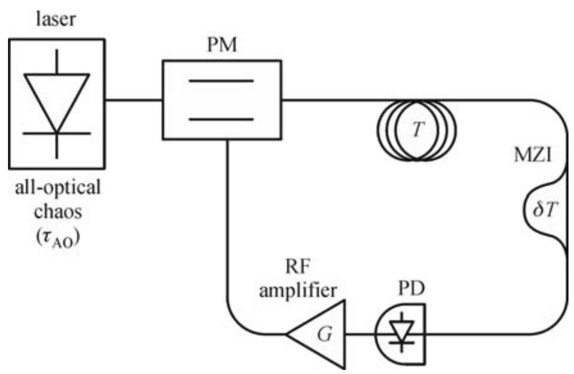

Fig. 9 Cascaded all-optical chaos and electro-optic phase-chaos systems for time delay concealment (Ref. [20]). PM: phase modulator; MZI: Mach-Zehnder interferometer; RF: radio frequency; PD: photodiode

transmitted signal when loops are coupled in parallel and each loop has a different differential delay time, so this system intrinsically conceals the internal delay time [22].

Most of the TDS concealment methods in electro-optic feedback chaotic systems have adopted the combined chaos configuration and the TDS concealment is achieved through time domain processing except for our proposed method in Ref. [19] where only a TDC module is introduced into the traditional feedback loop and the TDS concealment is achieved from frequency domain processing.

3.1.2 Chaotic complexity improvement

In order to further enhance the security of chaotic optical communications, except for the time delay concealment, increasing the chaotic complexity is another effective way. The security can be improved to a certain extent by using double masking [23], Manchester coding [24], combining all-optical and electro-optical feedback schemes [20]. For example, in the configuration of Figs. 10 and 11, digital key is a way to increase the complexity, so the combination of time delay concealment and digital key selectivity provides a large enhancement of security in chaotic optical communications [21,22]. In addition, an internal delay time in the configuration of Fig. 11 can also increase the chaotic complexity [22]. Besides, a QPSK electro-optic modulator in the configuration of Fig. 3 is a way to increase the chaotic complexity, because the nonlinearity originates from an integrated four-wave optical interferometer, involving two independent electro-optic modulation inputs [16]. In all, the chaotic complexity improvement is accompanied with the complexity enhancement of the chaos generation configuration, therefore also increases the difficulty of synchronization. Thus the method of increasing the chaotic complexity without complicating the system configuration and increasing the synchronization difficulty is highly desired.

3.2 System demonstration

Since chaotic synchronization was realized in the early 1990s [25,26], chaotic optical communications has become a hot topic to provide information security in physical layer [5,6,25–41]. Most of proposals are based on the nonlinear dynamics of semiconductor lasers, and the transmission rates of this approach has been limited to 2.5 Gb/s by the bandwidth of the semiconductor laser [6,38]. By comparison, the chaotic optical communications based on electro-optic feedback can support high bit rate attributed to the high bandwidth of modulators. 10 Gb/s data transmission has been achieved based on the electro-optic phase chaos system [6]. Except for the

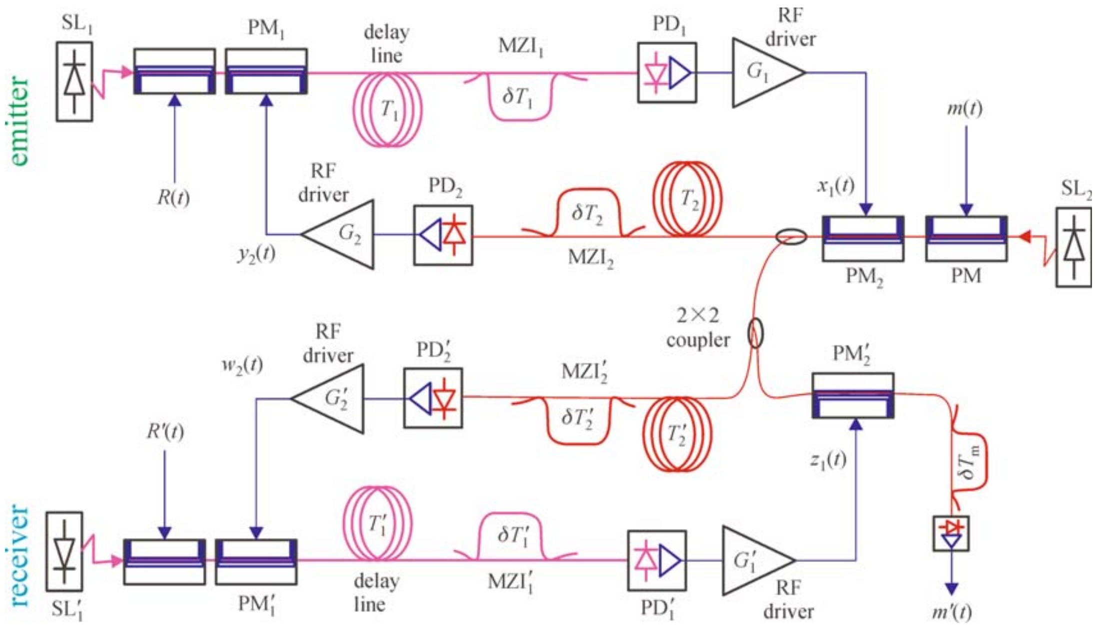

Fig. 10 Schematic of digital key introduction into phase chaos generator in serial configuration for time delay concealment (Ref. [21]). SL: semiconductor laser; PM: phase modulator; MZI: Mach-Zehnder interferometer; RF: radio frequency; PD: photodiode

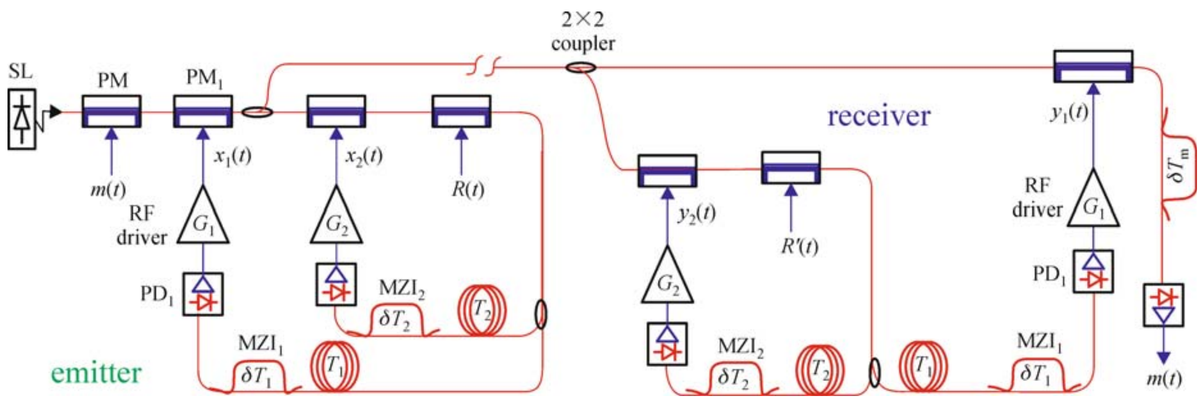

Fig. 11 Schematic of digital key introduced into phase chaos generator in parallel configuration for time delay concealment (Ref. [22]). SL: semiconductor laser; PM: phase modulator; MZI: Mach-Zehnder interferometer; RF: radio frequency; PD: photodiode

transmission speed, the transmission distance is also a key parameter to evaluate the system performance of chaotic optical communications. The chaotic signal is very sensitive to dispersion, therefore the transmission distance is limited to around 100 km in most of experimental demonstrations. Next, we will introduce the system demonstrations of chaotic optical communication in laboratory and field.

3.2.1 Laboratory demonstration

In 1998, Gregory D. Van Wiggeren and Rajarshi Roy demonstrated 10 MHz message transmission using erbium-doped fiber ring lasers based chaotic systems [25]. In 2001, S. Tang and J. M. Liu realized message encoding-decoding at 2.5 Gbit/s through synchronization of chaotic pulsing semiconductor lasers [35]. In 2002, Kenji Kusumoto and Junji Ohtsubo realized sinusoidal message transmission up to 1.5 GHz based on chaos synchronization in nonlinear systems of semiconductor lasers with optical feedback [37]. In 2004, Gastaud et al. improved the bit rate up to 3 Gbit/s in a modulator-based chaotic optical systems and bit error rate of 7×10^{-9} has been achieved after chaos synchronization. The masking capability of the chaotic optical carrier was observed to cover a flat RF spectrum over more than 20 GHz, therefore several tens of Gb/s bit rate is potential to be supported [41]. In 2005, Annovazzi-Lodi et al. realized 2.4 GHz standard TV signal transmission through an optical fiber link, which is the first demonstration of chaotic optical communications applied to “real-world” high-frequency signals [39]. In 2010, Argyris et al. realized 2.5 Gb/s data

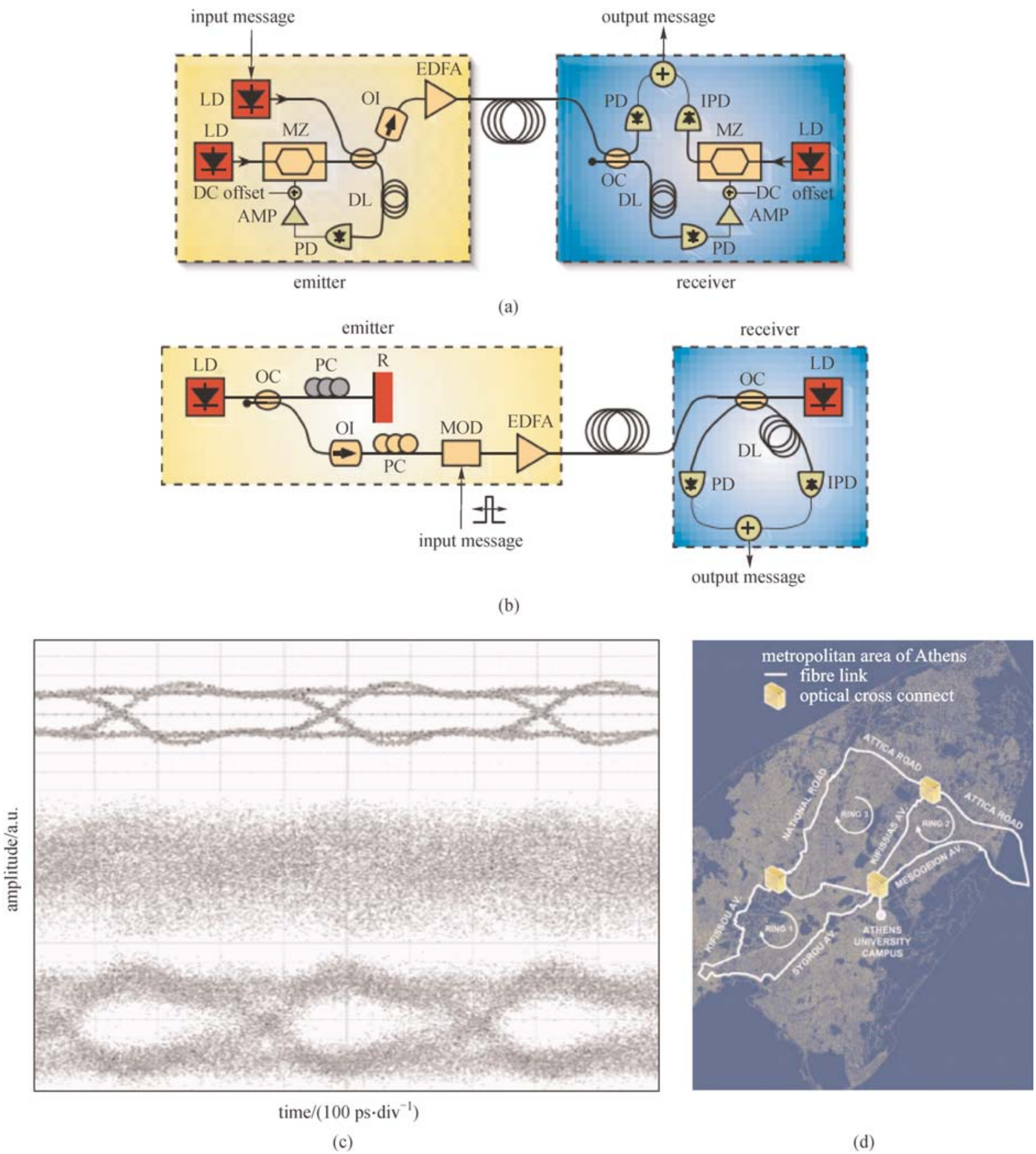

Fig. 12 Schematic of (a) electro-optical feedback; (b) the schematic of all-optical feedback; (c) eye diagrams in the electro-optic set-up, (d) field experiment of fiber transmission (Ref. [5]). LD: laser diode; MZ: Mach-Zehnder modulator; OI: optical isolator; EDFA: erbium-doped fiber amplifier; DL: delay line; AMP: amplifier; OC: optical coupler; PD: photodiode; IPD: inverse photodiode; PC: polarization controller; R: reflector; MOD: modulator

transmission using monolithic photonic integrated circuits (PICs) as chaos generator. In this scheme, only authorized counterparts, supplied with identical chaos generation PICs that are able to synchronize and reproduce the same chaotic carrier, can achieve 2.5 Gb/s transmission rates, with error rates below [40]. From the research progress, 10 Gb/s data transmission in chaotic optical communications is difficult to be achieved in the past years, which is mainly limited by the bandwidth of the electro-optic components and the synchronization difficulty at high bandwidth cases. With the bandwidth increase of the electro-optic components, such as lasers, modulators, photo-detectors and electrical amplifiers, and the development of advanced optical signal processing and digital signal processing techniques, chaotic optical communications with higher bit rate are potential to be achieved.

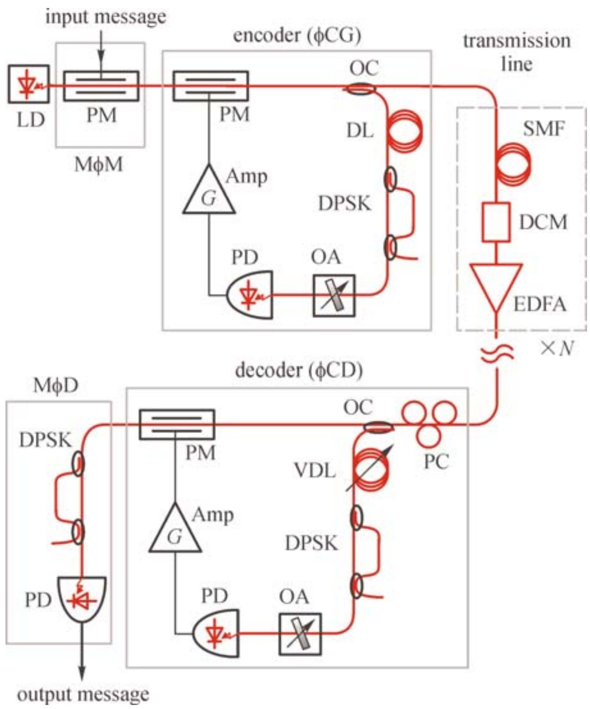

Fig. 13 Field demonstration of phase chaos based optical communications operated at 10 Gb/s bit rate (Ref. [6]). LD: laser diode; PM: phase modulator; OC: optical coupler; Amp: amplifier; PD: photodiode; DL: delay line; OA: optical attenuator; DPSK: differential phase-shifted-keying; SMF: single mode fiber; DCM: dispersion compensation module; EDFA: erbium-doped fiber amplifier; VDL: variable delay line; PC: polarization controller

3.2.2 Field demonstration

There have been two remarkable field demonstrations of chaotic optical communications to prove its feasibility in the real world. In 2005, the first field experiment using commercial optical networks was realized, and the transmission rates in the gigabit per second range were achieved, with corresponding bit-error rates below 10^{-7} and distance over 120 km [5]. Two schematics of experimental setup are shown in Fig. 12. Figures 12(a) and 12(b) show the modulator-based electro-optic feedback scheme and the laser-based all-optical feedback scheme respectively. Communication bit rates are mainly limited by the bandwidth of the chaotic carrier. The bandwidth is about 7 GHz in the electro-optic setup, while the bandwidth is about 5 GHz in the all-optical setup. Figure 12(c) shows the eye diagrams in the electro-optic set-up, where the upper trace is the message, the middle trace is the encoded signal and the bottom trace is the decoded message. Figure 12(d) shows the first field experiment of fiber transmission in metropolitan area network of Athens, which proved that chaotic optical communication can be used in real-world communication to provide information security.

Thanks to the proposal of electro-optic phase chaos in 2009 [17], 10 Gb/s chaos communications over more than 100 km fiber transmission on the all-optical fiber ring network installed in the city of Besancon, France was demonstrated in 2010 [6], which is the record data rate for chaos-based optical communications. The setup is depicted in Fig. 13, where the emitter performs differential phase-shifted-keying (DPSK) binary message modulation and chaotic phase masking, then the light from the emitter is sent to the receiver through an installed network fiber link, after that, the receiver first recovers the DPSK signal through phase chaos synchronization. At last, the DPSK demodulator retrieves the binary signal. The 10 Gb/s transmission rates over 100 km fiber transmission shows that this setup is superior to other popular architectures, which is probably attributed to the phase signal is more tolerant to fiber dispersion than intensity signal. With high-speed components and high-order modulation format such as QPSK, 40 Gb/s bit rate over 100 km fiber transmission is possible to be achieved based on this architecture.

4 Discussion and conclusion

After the record field demonstration of 10 Gb/s data transmission over 100 km fiber, there have been no further improvement on the transmission date rate and distance. From the analysis above, it is possible to further increase the transmission bit rate and extend the transmission distance using advanced components and signal processing techniques, but indeed the progress has been slowing down in recent several years, which we believe it is due to the security of chaotic optical communications still remains to be addressed. So after 2010, the researches in chaotic optical communications have been mainly focused on improving the security level either by concealing the time delay or increasing the chaotic complexity as introduced before. Once the security issue is solved, the research topics of chaotic optical communications will switch to the following three topics: increasing the chaotic transmission speed, extending the chaotic transmission distance and networking multiple chaotic nodes. The last topic is especially important because most of system demonstrations are based on point-to-point transmission, which cannot be used in many optical networks. After solving all the above problems, chaotic optical communications are ready for practical applications.

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