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Electro-optic intensity chaotic system with an extra optical feedback

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A R T I C L E I N F O

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A B S T R A C T

Electro-optic (EO) delay oscillators have been widely investigated for secure optical communication. To improve complexity and security, an EO intensity chaotic system with an extra optical feedback is proposed. Simulation results show that the proposed system can improve complexity. Moreover, it can effectively suppress the time delay analysis, and the suppression can be enhanced by increasing the optical feedback strength of our system. In addition, synchronization of the communication system in a chaotic modulation encryption scheme based on the proposed system is discussed.

1. Introduction

Information security remains a challenging subject for optical communication. Traditional software encryption techniques provide a certain degree of security, but their slow encryption rate fails to keep pace with the development of optical communication. Chaotic signal has high robustness and high privacy in data transmission. As a result, chaotic secure communication, a hardware encryption method for optical communication, has attracted many researchers' attention in the past two decades. It is a high-speed method compared with software encryption techniques, but its confidentiality remains to be improved [1]. Much research focuses on enhancing chaos and improving the security of optical chaotic systems since Argyris et al. [2] applied the optical chaotic systems to secure data transmission over 120 km of a commercial optical network.

More recently, optical nonlinear delayed feedback systems (ONDFSs), also known as Ikeda-based electro-optic (EO) systems, have been widely reported because of their hyperchaotic characteristics [3,4]. Such systems are typically constructed with EO delay devices [5–10]. EO setups have two advantages compared with electronic setups such as Lorenz or Chua's systems. First, they can generate chaotic optical carriers at rates above 10 Gb/s [11] for high-speed optical communication. Second, their high complexity has shown promise at more efficient encryption [9,11]. The complexity of ONDFSs depends on the feedback strength and extrema number of the nonlinear feedback function [3]. Moreover, the time delay in the feedback loop results in an infinite-dimensional phase space, which can lead to very high-dimensional chaotic dynamics. However, increasing the dimension is not necessary for security [12]. The ability of the eavesdropper to reveal the fundamental parameters of the system is of utmost importance. Therefore, delay recovery problems need to be addressed [13,14].

In a general case, a constant wave (CW) laser is used, and chaos merely relies on the nonlinearities of external component, namely, the Mach–Zehnder (MZ) modulator. In this respect, some schemes such as modulating the laser or changing the constant laser with a chaotic laser have been proposed [15–17]. [15] and [16] take advantage of the internal nonlinearities of the laser, whereas [17] has utilized the optical nonlinearities of an exogenic EO delay oscillator. Specifically, [15] uses the chaotic output to modulate the laser, which is referred to as a feedback method. They all achieved dynamic variations of feedback strength by converting the constant laser output into a variable output. Besides, multiple feedback [18], feedback coupling [19–21], or a hybrid method [22] has been suggested successively. Furthermore, modulating the time delay digitally [23] and multiple time delay strategy [24] are also demonstrated to be feasible schemes.

Hence, in this study, we proposed an optical chaotic system with an extra optical feedback based on the electro-optic intensity chaotic system (EOICS) [25]. The introduction of the optical feedback method reveals the complex variation of EO feedback strength, and a new delay is added. Without the modulation of the CW laser, the proposed system can enhance chaos by making use of the external nonlinearities again and will keep a concise mathematical expression. No additional costly component is needed, but it would be a highly efficient and feasible scheme.

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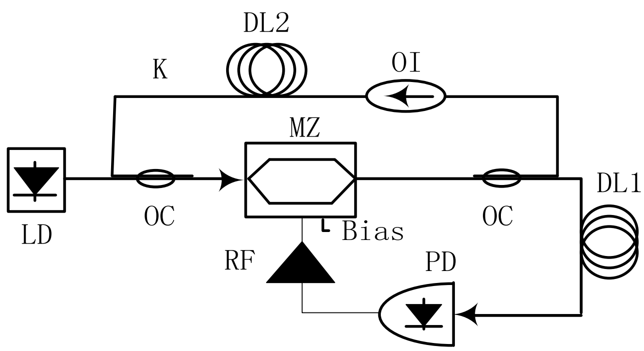

Fig. 1. Setup of EOICS with extra optical feedback, LD: laser diode, MZ: Mach–Zehnder modulator, DL: delay line, OC: optical coupler, PD: photodiode, RF: radio frequency driver.

2. System and mathematical model

Fig. 1 illustrates the schematic diagram of the proposed optical chaotic system. The proposed system differs from the system depicted in [5]. In the proposed system, we add an optical fiber to lead the output of the MZ modulator to feed back to its optical input with another delay T_{D2} in the loop. An optical isolator (OI) is used to ensure unidirectional optical feedback. As a result, it can be regarded as a delayed chaotic system with a variable parameter, which implies the improvement in complexity and security compared with [5].

As shown in Fig. 1, the light from the output of the MZ modulator is coupled with the light from the laser diode (LD) of power P_0 by a 2×2 fiber coupler and then modulated by the MZ modulator. The electrical input of MZ modulator is the radio-frequency (RF) driver's output voltage $V(t)$ and biased with a constant voltage V_B. The MZ output is written as $P_{in}(t) \cdot \cos^2[\frac{\pi V(t)}{2V_{\pi RF}} + \frac{\pi V_B}{2V_{\pi DC}}]$, where $V_{\pi RF}$ and $V_{\pi DC}$ indicate the RF half-wave voltage and bias electrode half-wave voltage, respectively, considering a variable optical input $P_{in}(t)$. The output light is split by another 2×2 fiber coupler into two beams, which are injected into the electro-optical feedback loop and optical feedback loop respectively. The electro-optical feedback loop contains an optical fiber delay line of delay time T_{D1}, a photodiode (PD) with responsivity s to detect and convert the optical signal into an electrical signal, and an RF driver with gain g and a band-pass filter with low cutoff frequency f_L and high cutoff frequency f_H. The output of the RF driver is the electrical voltage $V(t)$ for the Mach–Zehnder electrode. Besides, the electro-optical feedback loop considers the overall attenuation A, whereas the optical feedback loop considers an attenuation K. We consider $x(t) = \frac{\pi V(t)}{2V_{\pi RF}}$. Then, the system's dynamics can be modeled by the following delay integro-differential equation:

$$\begin{cases} x(t) + \sigma \dfrac{d}{dt}x(t) + \dfrac{1}{\theta}\displaystyle\int_{t_0}^{t} x(s)ds = P_{in}(t - T_{D1}) \cdot \cos^2[x(t - T_{D1}) + \phi] \cdot G \\ P_0 + K \cdot P_{in}(t - T_{D2}) \cdot \cos^2[x(t - T_{D2}) + \phi] = P_{in}(t) \end{cases}, \tag{1}$$

where $G = \frac{\pi A s g}{2V_{\pi RF}}, \sigma = \frac{1}{2\pi f_H}, \theta = \frac{1}{2\pi f_L}, \phi = \frac{\pi V_B}{2V_{\pi DC}}$.

For numerical simulations, we introduce dimensionless time $\frac{t}{\sigma}$, where the time has been scaled with σ. Then, Eq. (1) can be rewritten as follows:

$$\begin{cases} x(t) + \dfrac{d}{dt}x(t) + \varepsilon\displaystyle\int_{t_0}^{t} x(s)ds = P_{in}(t - T_1) \cdot \cos^2[x(t - T_1) + \phi] \cdot G \\ P_0 + K \cdot P_{in}(t - T_2) \cdot \cos^2[x(t - T_2) + \phi] = P_{in}(t) \end{cases}, \tag{2}$$

where $\varepsilon = \frac{\sigma}{\theta}, T_1 = \frac{T_{D1}}{\sigma}, T_2 = \frac{T_{D2}}{\sigma}$.

We set the parameters in Eq. (1) at values compatible with those of the experiential setup according to [5], that is, $\sigma = 25$ ps, $T_{D1} = 30$ ns, $T_{D2} = 25$ ns, $\theta = 5\,\mu$s, and $\Phi = -\pi/4$ for the symmetric case [26]. Accordingly, the corresponding parameters in Eq. (2) are $\varepsilon = 5 * 10^{-6}$, $T_1 = 1200$, $T_2 = 1000$, and Φ is constant. G is constrained by the device, and P_0 is typically 5 mW. In the simulations, we keep $G = 1000$ and $K = 0.8$ for comparison. The following conclusions are obtained from the numerical simulations.

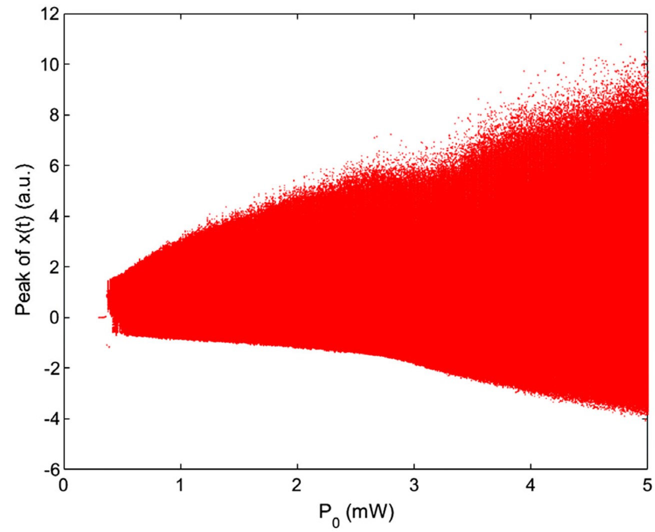

Fig. 2. Bifurcation diagram of the EOICS with extra optical feedback.

3. Complexity and security

The simulations of Eq. (2) were conducted with a fourth-order Runge–Kutta algorithm, and the time step used for the numerical integration is 5 ps. The results are obtained by integrating over a time of 35 μs which is seven times longer than the slowest time scale θ of the model. The dynamic optical input $P_{in}(t)$ is equal to the laser's power P_0 without the optical feedback loop. Thus, the system in Eq. (1) is similar to that in [3], which is often referred to as nonlinear delay differential equations. $P_0 * G$ is usually considered the bifurcation parameter as it represents the strength of the nonlinear function, which plays an important role in the chaotic behavior with high complexity. The bifurcation diagram of $x(t)$ versus P_0 is plotted in Fig. 2. The diagram shows that a broader parameter range is obtained because it is chaotic in the range of $P_0 = 0.55 - 5$ mW.

To give insight into the enhancement of chaos, the largest Lyapunov exponents [27] (LLEs) have been calculated for different P_0, and a comparison with the system without extra optical feedback is depicted in Fig. 3(a). As the figure displays, it dramatically rises to a relatively large positive value at $P_0 = 0.55$ in the proposed system, which is corresponding to the burst in the bifurcation diagram and implies the generation of chaos. By contrast, the general EOICS starts to insignificantly increase at $P_0 = 1.0$ and speeds up at $P_0 = 2.4$. The dynamic behavior such as Hopf bifurcation [5,26,28] may exist when the LLE holds a low positive value. The parameter K is introduced in Fig. 3(b). The strong optical feedback strength contributes to the enhanced chaotic behavior as it obtains obviously larger LLE. However, the optical feedback strength cannot be too large; otherwise, the output becomes unstable. A reasonable explanation is that the large feedback strength could cause a large perturbation in the input, thus producing unstable dynamics. That is to say, parameter K must be kept in a certain range.

Permutation entropy (PE) is also an effective measure of complexity. It is calculated completely according to the output data. But the calculation of LEs in this paper must know the system equations in advance. Fortunately, it is easily implemented and can be computed much faster. Hence, we compare the PE of EOICSs with and without extra optical feedback in Fig. 4. As suggested in [29], we select the