

The synchronized characteristics of the incoherent optical feedback chaotic system

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Based on the theoretical model of the synchronization system with incoherent optical feedback, the influence of the internal parameter mismatch on the synchronized characteristics of the chaotic system has been investigated. The result shows that the chaotic system with incoherent optical feedback can be realized more easily than the complete synchronized system, and has higher security than injection locking synchronization system. Using encoding of chaos shift keying, the message can be hidden efficiently during the transmission in the system and decoded easily in receiver.

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1. Introduction

Laser chaotic secure communication is a developing new research field in recent years [1-9]. As one of the methods to realize the chaos synchronization, the optical feedback system, which includes the coherent optical feedback and incoherent optical feedback, has received considerable attention. According to the system tolerance to parameters mismatch, the coherent optical feedback can be divided into two categories: complete synchronization and injection-locking synchronization. Complete synchronization has high secrecy, but is too sensitive to the parameters mismatch. If there exists small oscillating frequency detuning between the emitting laser and receiving laser, the synchronized performance will greatly decrease. Therefore complete synchronization requires an accurate oscillating frequency match between the emitting laser and the receiving laser, which is difficult to realize in practice. As for the injection-locking synchronization, it has good tolerance to parameters mismatch. However, the sensitivity lowering to parameter mismatch will lead to the security decline. In recent years, the incoherent optical feedback synchronization system is presented by some scholars [10-13]. Since the feedback light of the emitting laser and the injection light of the receiving laser affect only the carriers but not the light field, the frequency detuning will not affect the system synchronization. Therefore, compared with the complete synchronization coherent optical feedback, incoherent optical feedback chaotic synchronization is easier to achieve. In this paper, based on the theoretical model of the incoherent optical feedback synchronization system, the influence of the internal parameters mismatch on the synchronized characteristics of the chaotic system has been investigated. Compared with two styles of chaotic system with coherent

optical feedback, the chaotic system with incoherent optical feedback is not only easier to put into practice than the complete synchronized system but also has higher security than injection-locking synchronization system. Adopting encoding of chaos shift keying (CSK), the message can be hidden efficiently during the transmission and decoded easily in receiver.

2. Theory

Fig. 1 is the schematic of the incoherent optical feedback chaos synchronization system. The transmitter and receiver consist of two single-mode semiconductor lasers (LD1, LD2). Message encoding is achieved by chaos shift keying in transmitter. The horizontally polarized beam emitted from LD1 is firstly rotated 45° by a Faraday rotator (RTO), then incidents on a partially reflecting mirror (PM). On the one hand, the reflected beam is re-injected into the RTO, which is rotated an additional 45° . So the horizontally polarized beam becomes vertically polarized beam, and is feedback into LD1. On the other hand, the transmitted beam enters a faraday isolator (ISO1) which rotates the beam another 45° to vertical. After passing through a high-reflectivity steering mirrors (HR), the vertically polarized beam strikes a plate beam splitter (BS). Then the beam is split into two parts by BS, one part is coupled into LD2. In the same way, the horizontally polarized beam emitted from LD2 is rotated 90° after passing through two faraday isolators (ISO2, ISO3). The message can be decoded by subtracting the rotated output of the receiver from another part of BS.

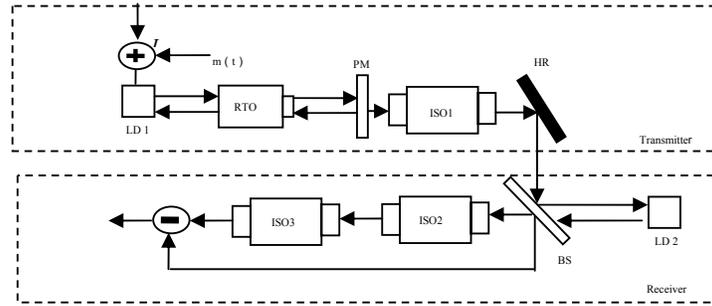


Fig. 1. Schematic of the incoherent optical feedback chaos synchronization system.

The dynamics of transmitter and receiver can be described by the following rate equations [10]:

$$\frac{dS_t(t)}{dt} = (G_t - \frac{1}{\tau_{pt}})S_t(t) + \beta_t N_t(t) + F_t(t) \quad (1)$$

$$\frac{dN_t}{dt} = \frac{I_t(t)}{e} - \frac{N_t(t)}{\tau_{\square\square}} - G_t[S_t(t) + kS_t(t - \tau)] \quad (2)$$

$$\frac{dS_r}{dt} = (G_r - \frac{1}{\tau_{pr}})S_r(t) + \beta_r N_r(t) + F_r(t) \quad (3)$$

$$\frac{dN_r}{dt} = \frac{I_r(t)}{e} - \frac{N_r(t)}{\tau_{\square\square}} - G_r[S_r(t) + \sigma S_t(t - \tau_c)] \quad (4)$$

where the subscripts t and r denote the transmitter and receiver, respectively, τ_p and τ_s are the photon lifetime and the carrier lifetime, respectively, I is the injection current, e is the electronic charge, N is the carrier number, S is the photon number, β is the spontaneous emission rate, τ and τ_c are the external cavity round-trip time and the transmission time of injection signal, k is the feedback strength of the transmitter, σ is the coupling strength at the receiver, $G = G_N(1 - \epsilon S)(N - N_0)$ is the gain (G_N is gain coefficient, ϵ is the gain saturation coefficient, N_0 is the transparency carrier number), F is a Langevin noise, which accounts for stochastic fluctuations arising from spontaneous-emission processes and satisfies the relations $\langle F(t)F(t') \rangle = 2NS\beta\delta(t - t')$.

3. Results and discussion

For simplifying numerical calculation, we ignore Langevin noise and assume that the coupling strength at receiver exactly matches the feedback strength of the transmitter and the transmission time of injection signal is equal to the external cavity round-trip time, i.e.,

$k = \sigma, \tau = \tau_c$. Both of the injection currents of the two lasers are biased at $I = 1.8I_{th}$, where I_{th} is the threshold current of laser. The other parameters values used in the calculation are chosen as: $\tau_p = 2 \times 10^{-9} s$, $\tau_s = 2 \times 10^{-6} s$, $k = \sigma = 0.41$, $G_N = 1 \times 10^4 s^{-1}$, $N_0 = 1.1 \times 10^8$, $\epsilon = 7.5 \times 10^{-8}$, $\beta = 5 \times 10^3 s^{-1}$, $\tau = \tau_c = 9 \times 10^{-9} s$. The rate equations (1)-(4) can be solved using the fourth-order Runge-Kutta algorithm, and then the output time series of the transmitter and the receiver as well as their phase portrait can be obtained, as shown in Fig. 2. From these diagrams, it can be seen that both of the outputs of transmitter and receiver are chaotic.

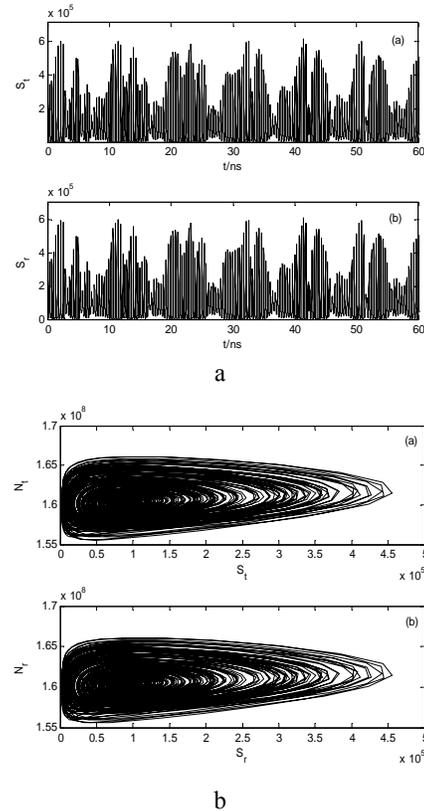


Fig. 2. Time series and phase portrait for (a) the transmitter and (b) the receiver.

The synchronization quality between the transmitter and the receiver can be evaluated by the correlation function [14]:

$$C(\Delta t) = \frac{\langle [S_t(t) - \langle S_t(t) \rangle][S_r(t + \Delta t) - \langle S_r(t) \rangle] \rangle}{\sqrt{\langle |S_t(t) - \langle S_t(t) \rangle|^2 \rangle \langle |S_r(t) - \langle S_r(t) \rangle|^2 \rangle}} \quad (5)$$

where Δt is the time shift, the expectation denoted by $\langle \rangle$ is evaluated via a time average. A correlation value of unity indicates that the transmitter and receiver optical field are identical, and the synchronization quality becomes worse with the decrease of the absolute value of C . The variation of correlation coefficient with the time delay has been shown in Fig. 3. When the time shift is zero, the correlation coefficient achieves the maximum value $C_{max}=1$, i. e., the output of the receiver can perfectly synchronize with the transmitter.

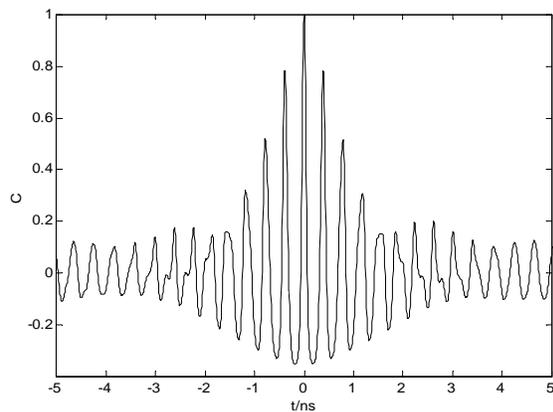


Fig.3. Transmitter-receiver correlation C as a function of the time shift.

The sensitivity of the system to the parameters mismatch will directly affect the security of the communication system. With the increase of mismatch tolerance, the system can be implemented more easily but the system security will be decreased inevitably. Although the external parameter mismatch is easier to control, it is difficult to control the internal parameters mismatch such as the photon lifetime, the carrier lifetime, the gain coefficient, the linewidth enhancement factor, and spontaneous emission factor mismatch. In this paper, we focus on the tolerance of the incoherent feedback system to three typical internal parameters mismatch (the photon lifetime, the carrier lifetime and the gain coefficient), and obtained result will be compared with that of the coherent feedback system.

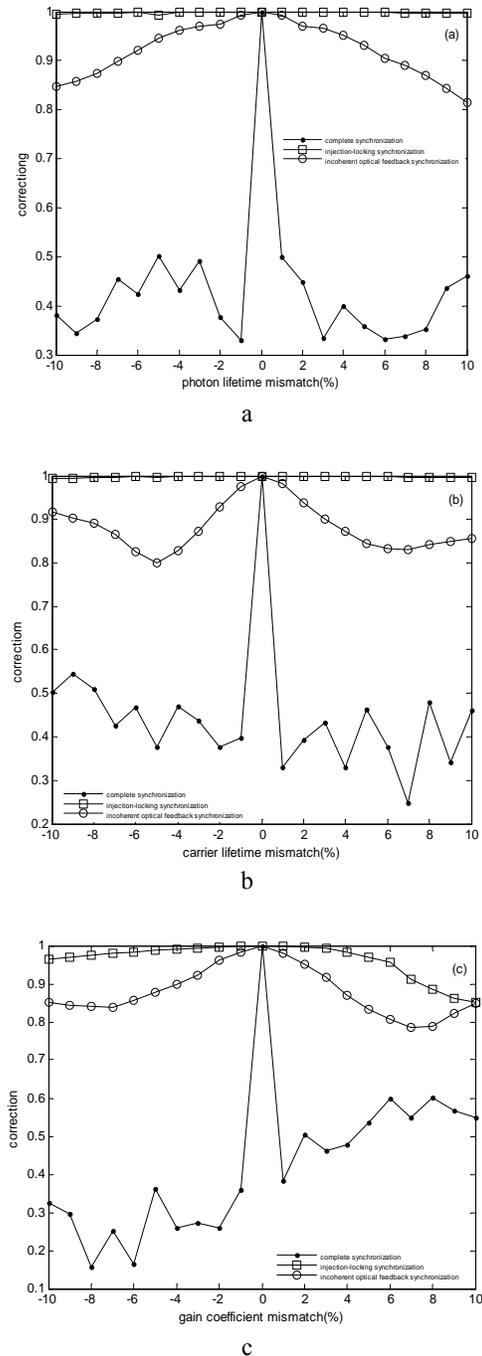


Fig. 4. C_{max} as a function of (a) photon lifetime mismatch, (b) lifetime mismatch, and (c) gain coefficient mismatch.

Fig. 4 shows the variation of the maximum of cross-correlation coefficient C_{max} with the parameters mismatch. All the variation range of the parameters mismatch is from -10% to +10%. For a coherent feedback system with complete synchronization (denoted by dot), synchronization performance is ultrahigh sensitive to parameters mismatch, the synchronization coefficient will decrease drastically when the parameters mismatch

increase from 0 to 1%. So complete synchronization coherent feedback system requires an accurate match between transmitter and receiver, which is difficult to be realized in practice. For an injection-locking coherent feedback system (denoted by square), the variation of synchronization coefficients is not obvious, the system can maintain high-quality synchronization performance within a large mismatch range. So the signal is relatively easy to be eavesdropped because the signal can be recovered even if the received laser is very different from the transmitter. For an incoherent optical feedback system (denoted by hollow circle), it has higher tolerance to parameter mismatch than complete synchronization and the system synchronization performance is not affected by the frequency detuning, so the system can be carried out more easily than complete synchronization coherent feedback system. Meanwhile, incoherent optical feedback system still keeps some sensitivity to the parameter mismatch and has higher security than injection-locking synchronization.

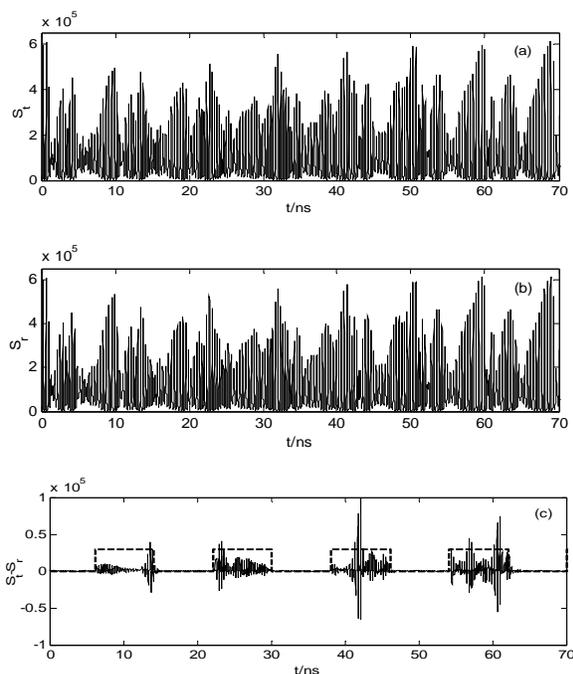


Fig. 5. Output time series of (a) the transmitter and (b) the receiver, and (c) the subtracted signal.

In this paper, message is assumed to be encoded by means of chaos shift keying (CSK) [15]. For a CSK scheme, the digital message is added in the system by modulating the current of the transmitter. The current of transmitted laser can be shown as $I[1+Af(t)]$, where I is still $1.8I_{th}$, A is the amplitude of modulation and is assumed to be 0.01, $f(t)$ is the square wave signal and its value is 0 or 1. So the current of the transmitter will be located at one of two distinct values depending on the $f(t)$ is 0 or 1. The current of the received laser is biased at a

fixed value I . Fig. 5(a) and (b) are the output time series of the transmitter and receiver respectively for a 125-Mbit/s message transmission. From these diagrams, it can be seen that the message is hidden efficiently in the system. The signal subtracted through calculation the output deviation between the transmitter and receiver has been given by solid line in Fig. 5(c). For the time interval where $S_t - S_r$ is 0, the output of receiver is the same as the output of the transmitter and the chaos synchronization achieves. So, it can be deduced that the message must be 0. For the time interval where $S_t - S_r$ is not equal to 0, the output of receiver is different from the output of the transmitter and the chaos synchronization does not realize, so the message must be 1. Therefore, the square wave signal can be obtained. The final recovered signal has been shown by the broken line in Fig. 5(c), which indicates that the message can be decoded perfectly.

4. Conclusions

Based on the theoretical mode of the incoherent optical feedback system, the influences of the internal parameters mismatch on the synchronized characteristics of the chaotic system have been investigated. Comparing with two styles of chaotic system with coherent optical feedback, the chaotic system with incoherent optical feedback is not only easier to put into practice than the complete synchronized coherent optical feedback system but also has higher security than injection-locking synchronization coherent optical feedback system. Using encoding of chaos shift keying, the message can be hidden efficiently during the transmission and decoded easily in the receiver.

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References

- [1] G. Q. Xia, Z. M. Wu, J. G. Wu, *Opt. Express* **13**, 3445 (2005).
- [2] J. Liu, H. Chen, S. Tang, *IEEE J. Quantum Electron.* **38**, 1184 (2002).
- [3] Y. Liu, H. F. Chen, J. M. Liu, P. Davis, T. Aida, *IEEE Trans. on Circuits and System* **48**, 1484 (2001).
- [4] M. W. Lee, K. A. Shore, *IEEE/OSA J. Lightwave Technol.* **23**, 1068 (2005).
- [5] H. G. Winful, L. Rahman, *Phys. Rev. Lett.* **65**, 1575 (1990).

- [6] Y. Liu, Y. Takiguchi, P. Davis, T. Aida, S. Saito, *Appl. Phys. Lett.* **80**, 4306 (2002).
- [7] A. Murakami, K. Kawashima, K. Atsuki, *IEEE J. Quantum Electron.* **39**, 1196 (2003).
- [8] Y. Liu, Y. Takiguchi, P. Davis, T. Aida, S. Saito, *Appl. Phys. Lett.* **80**, 4306 (2002).
- [9] D. Z. Zhong, G. Q. Xia, Z. M. Wu, *J. Optoelectron. Adv. Mater.* **6**, 1233 (2004).
- [10] F. Rogister, A. Locquet, *Opt. Lett.* **26**, 1486 (2001).
- [11] P. Ju, P. S. Spencer, *IEEE/OSA J. Lightwave Technol.* **23**, 2513 (2005).
- [12] D. W. Sukow, K. Blackburn, A. R. Spain, K. J. Ba, *Opt. Lett.* **29**, 2393 (2004).
- [13] J. M. Saucedo Solorio, D. W. Sukow, D. R. Hicks, A. Gavrielides, *Opt. Commun.* **214**, 327 (2002).
- [14] S. Tang, J. M. Liu, *IEEE J. Quantum Electron.* **39**, 708-715 (2003).
- [15] J. M. Liu, H. Chen, S. Tang, *IEEE J. Quantum Electron.* **38**, 1184-1194 (2002).

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