

Comparison of closed-loop and open-loop in incoherent optical feedback chaos synchronization system

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Based on the theoretical model of semiconductor lasers subject to incoherent optical feedback, the chaos synchronization characteristics and communication performances under closed-loop and open-loop schemes are numerically investigated. The results show that, compared with those that happen for closed-loop scheme, better performance of message decoding and less sensitivity to parameters mismatch can be obtained for open-loop scheme. These results are opposite to the case in coherent optical feedback chaos synchronization system.

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1. Introduction

In recent years, chaos synchronization and secure communication based on semiconductor lasers (SLs) have attracted considerable attention [1-24]. Compared with electrical chaos communication, optical chaos secret communication has some unique virtues such as higher security, broader signal bandwidth and greatly enhanced signal transmission capability. A semiconductor laser, when subjected to one or more perturbations such as optical feedback, optical injection, optoelectronic feedback and optical modulation, can display chaotic output under suitable operating conditions. If two SLs can realize good chaos synchronization, messages masked in the chaotic carrier can be extracted at the receiver by using the chaos filtering effect. Relevant studies showed that Gbit/s messages could be encoded and decoded within a highly dimensional chaotic carrier by using a pair of unidirectional coupled semiconductor lasers subject to coherent optical feedback or injection [4–8]. However, Frequency detuning between the free-running frequencies of the transmitter and receiver lasers degrades the synchronization performance [18]. Therefore, it is important to investigate alternative cryptographic schemes that have relative tolerance to frequency detuning. Based on this consideration, the incoherent optical feedback synchronization system is presented by some scholars [13-16]. During such system, since the feedback and the injection light affect only the carriers but not the light field, the frequency detuning will only have small influence on the system synchronization. Recently, chaos

synchronization and communication of semiconductor lasers with incoherent optical feedback have been investigated under open-loop scheme [13-16]. However, to our knowledge, there were no reports on the relative results under closed-loop scheme. In this paper, we numerically study the synchronization and the message decoding of incoherent optical feedback semiconductor laser under closed-loop and open-loop schemes, and compare their relevant performances under these two schemes.

2. Model

Fig. 1 is the schematic of the systematical configuration. The linearly polarized output field of the transmitter laser first undergoes a 90° polarization rotation through an external cavity formed by a Faraday rotator (FR) and a mirror, and then split into two parts by a non-polarizing beam splitter (BS). One part is fed back into the transmitter laser, and the other part is injected into the receiver laser. Under this circumstance, the polarization directions of the feedback and injection fields are orthogonal to those of transmitter and receiver output fields. In other words, the transmitter laser is subjected to incoherent feedback, whereas the receiver laser is subject to incoherent feedback and incoherent injection. An optical isolator (ISO) shields the transmitter from parasitic reflections from the receiver. As shown in Fig. 1, one can investigate the closed-loop or open-loop scheme by using or discarding the part with dash-dot frame of this diagram,

respectively. If necessary, one can place a linear polarizer (LP) between the Faraday rotator and the mirror to prevent

coherent feedback induced by a second round trip in the external cavity.

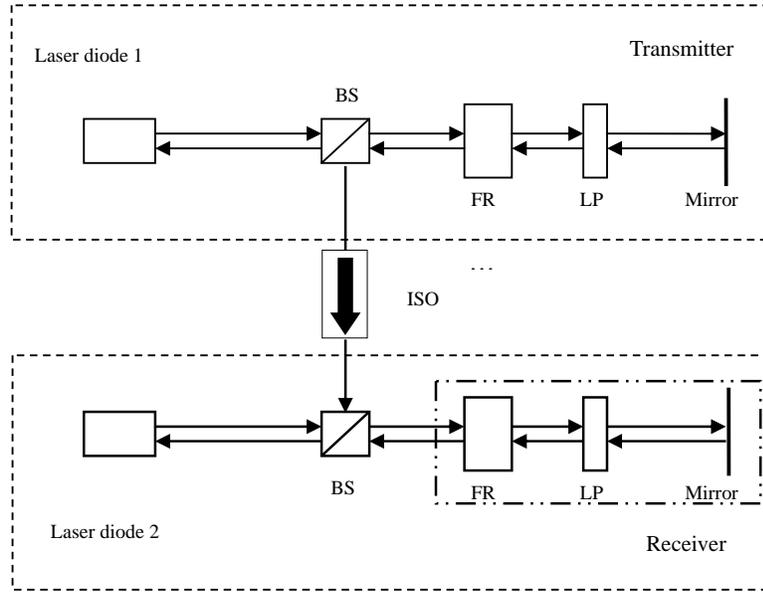


Fig.1. Schematic of the incoherent optical feedback chaos synchronization system. BS: beam splitter; FR: Faraday rotator; LP: linear polarizer; ISO: optical isolator.

In such a scheme, the rate equations can be modified as [13]

$$\frac{dP_1}{dt} = \left(G_1 - \frac{I}{\tau_{p1}} \right) P_1(t) + \beta_1 N_1(t) + F_1(t) \quad (1)$$

$$\frac{dN_1}{dt} = \frac{I_1(t)}{e} - \frac{N_1(t)}{\tau_{s1}} - G_1 [P_1(t) + \kappa_1 P_1(t - \tau_1)] \quad (2)$$

$$\frac{dP_2}{dt} = \left(G_2 - \frac{I}{\tau_{p2}} \right) P_2(t) + \beta_2 N_2(t) + F_2(t) \quad (3)$$

$$\frac{dN_2}{dt} = \frac{I_2(t)}{e} - \frac{N_2(t)}{\tau_{s2}} - G_2 [P_2(t) + \kappa_2 P_2(t - \tau_2) + \sigma P_1(t - \tau_c)] \quad (4)$$

where the subscripts 1, 2 stand for the transmitter and receive laser, respectively, P is the photon number, N is the carrier number in the active region of laser, τ_p , τ_s , I and ε are the photon lifetime, the carrier lifetime, the injection current and the gain saturation coefficient of laser, respectively, e is the electronic charge, F is a Langevin noise that accounts for stochastic fluctuations arising from spontaneous-emission processes. The Langevin noise satisfies the relation $\langle F(t)F(t') \rangle = 2NP\beta\delta(t-t')$, where β is the spontaneous emission rate. The operating parameters κ , τ , and σ are the strength and the delay of the feedback at the transmitter and the coupling strength at the

receiver, respectively. The transmission time of injection signal is τ_c . The gain is given by $G = G_N (I - \varepsilon)(N - N_0)$, where N_0 is the value of N at transparency, G_N is the gain coefficient. Based on the above equations, the numerical investigations can be performed.

To specifically describe the synchronization quality between two lasers, one usually uses following cross-correlation function [3]:

$$C(\Delta t) = \frac{\langle [P_1(t) - \langle P_1(t) \rangle][P_2(t + \Delta t) - \langle P_2(t) \rangle] \rangle}{\langle [P_1(t) - \langle P_1(t) \rangle]^2 \rangle^{1/2} \langle [P_2(t) - \langle P_2(t) \rangle]^2 \rangle^{1/2}} \quad (5)$$

where P_1 and P_2 represent the transient output intensity of the transmitter and receiver lasers, respectively, Δt is a time shift between laser outputs, the brackets $\langle \cdot \rangle$ represent the time average. The larger the $|C|$ is, the better the synchronization characteristics between two lasers will be. If $C=1$, the system achieves completely chaos synchronization.

3. Results and discussion

The rate equations (1)-(4) can be solved numerically by the fourth-order Runger-Kutta method. During the calculations, the used data are: $\tau_p = 2\text{ps}$, $\tau_s = 2\text{ns}$, $G_N =$

$1 \times 10^4 \text{ s}^{-1}$, $N_0 = 1.1 \times 10^8$, $\beta = 5 \times 10^3 \text{ s}^{-1}$, $\tau_c = \tau = 9 \times 10^{-9} \text{ s}$ and $\varepsilon = 7.5 \times 10^{-8}$.

Fig. 2 shows the transient output intensity and cross-correlation function of the two SLs under the open-loop and closed-loop schemes, respectively. In order to achieve completely chaos synchronization, the optimal

conditions ($\kappa_1 = \sigma + \kappa_2$ for closed-loop and $\kappa_1 = \sigma$ for the open-loop scheme) are taken into account so that parameters $\kappa_1 = \sigma = 0.41$, $\kappa_2 = 0$ for open-loop and $\kappa_1 = 0.41$, $\kappa_2 = 0.27$, $\sigma = 0.14$ for closed-loop are selected. From this diagram, it can be seen that the output of the lasers is irregular and noise-like sub-nanosecond pulse waveform.

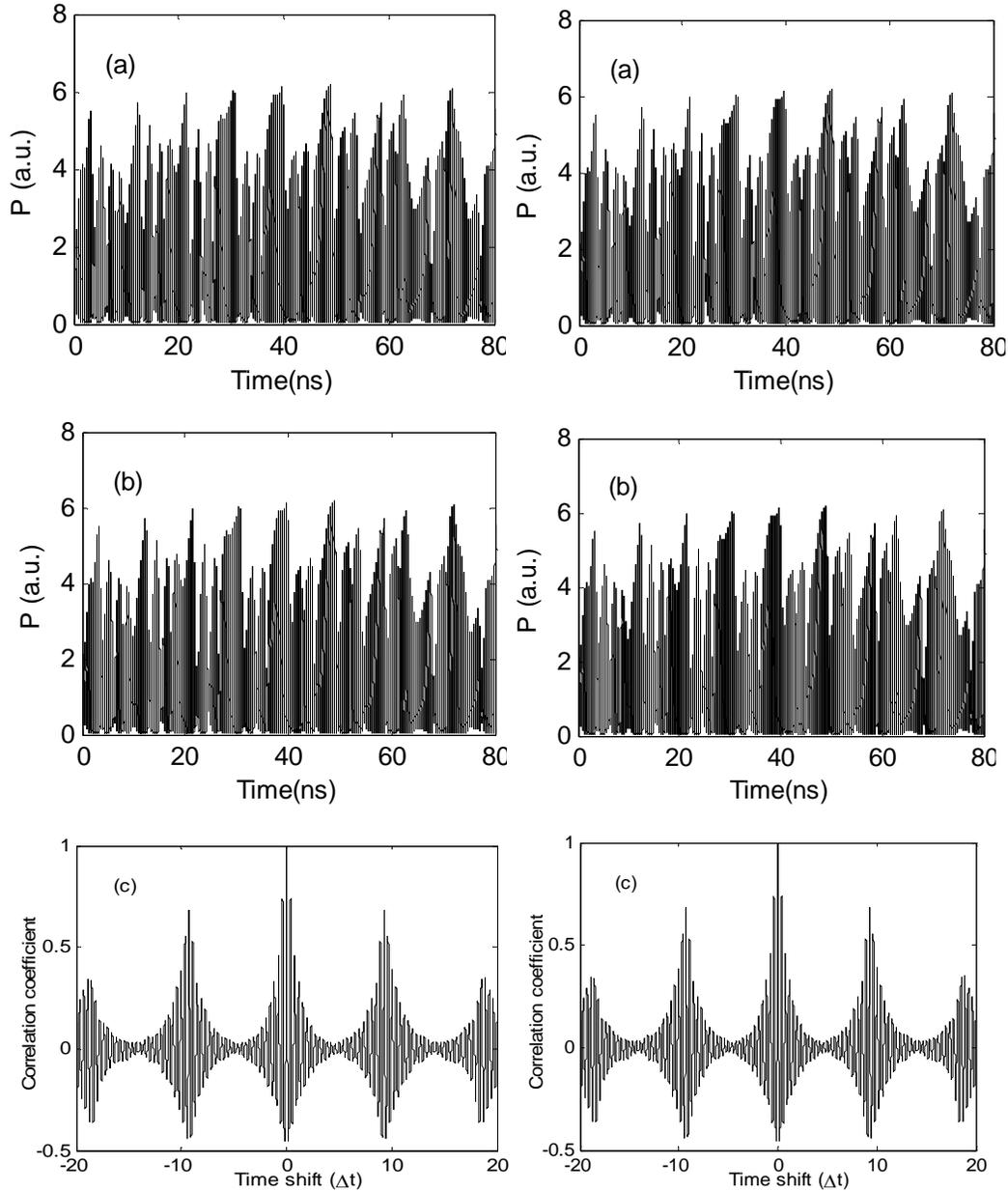


Fig. 2. Chaotic waveform of the transmitter (a), chaotic waveform of the receiver (b) and cross-correlation function between the two lasers, where the left and right volumes is corresponding to open-loop and closed-loop schemes, respectively.

Calculations also show that if the system operates beyond the optimal conditions, an obvious degradation of the synchronization will occur under both two schemes.

Moreover, even though this optimal condition is satisfied, the synchronization quality is related to the value of the coupling coefficient. Under both open-loop and

closed-loop schemes, the minimum necessary coupling coefficient to reach a correlation coefficient of 0.9, increases with the increase of the feedback strength of transmitter laser. For above given parameters, the minimum coupling coefficient is 0.26 for the open-loop and 0.07 for the closed-loop. In other words, the closed-loop scheme has a larger coupling coefficient

window than the open-loop one [10], which is in agreement with the case of coherent optical feedback [4].

Fig. 2 is obtained under this case that these two lasers have identical internal parameters, which is impossible to reach in practice. Therefore, it is needed to the influence of the parameters mismatch between transmitter and receiver on the synchronization.

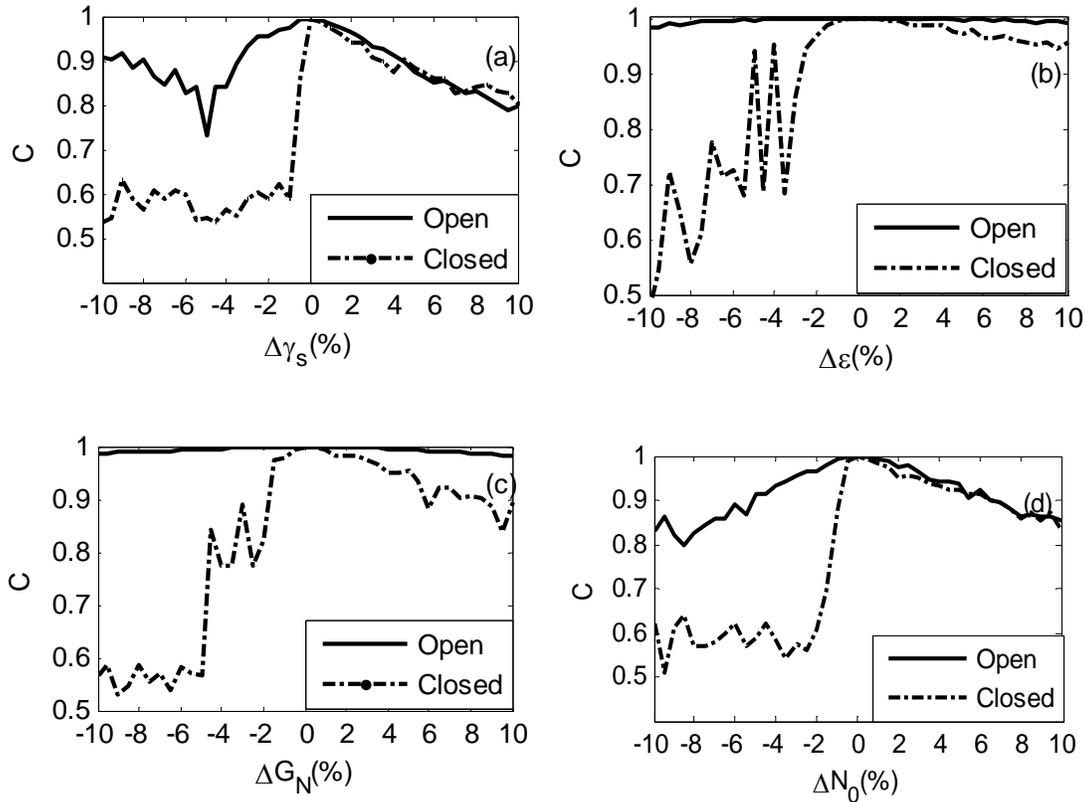


Fig. 3. Maximum of the cross correlation coefficients as a function of different mismatched parameters, where (a) carrier loss, (b) gain saturation coefficient, (c) gain coefficient, and (d) transparency carrier number.

Fig. 3 shows the variation of the maximum of cross-correlation coefficient C with the different mismatched parameters (carrier loss, gain saturation coefficient, gain coefficient and transparent carrier number). From these diagrams, it can be seen that the open-loop scheme is less sensitive to parameters mismatch than the closed-loop one. Correlation coefficients can reach about 0.9 within a 5% of parameters mismatch range under the open-loop, while it happens within a relative small range for the closed-loop.

Finally, we will give a simple comparison of the communication performance between the closed-loop and open-loop schemes.

Message is assumed to be encoded by means of chaos shift keying (CSK) [20], in which the digital message is added upon the system by modulating the current of the transmitter. Here, the modulation frequency is $f=500\text{MHz}$ and the modulation depth is $m = 0.01$. Fig. 4 displays the encoding and decoding message under identical parameters. From these diagrams, it can be seen that message can be recovered effectively under both schemes, where open-loop scheme shows better performance than closed-loop scheme. This result is in disagreement with the case of coherent optical feedback [4, 12].

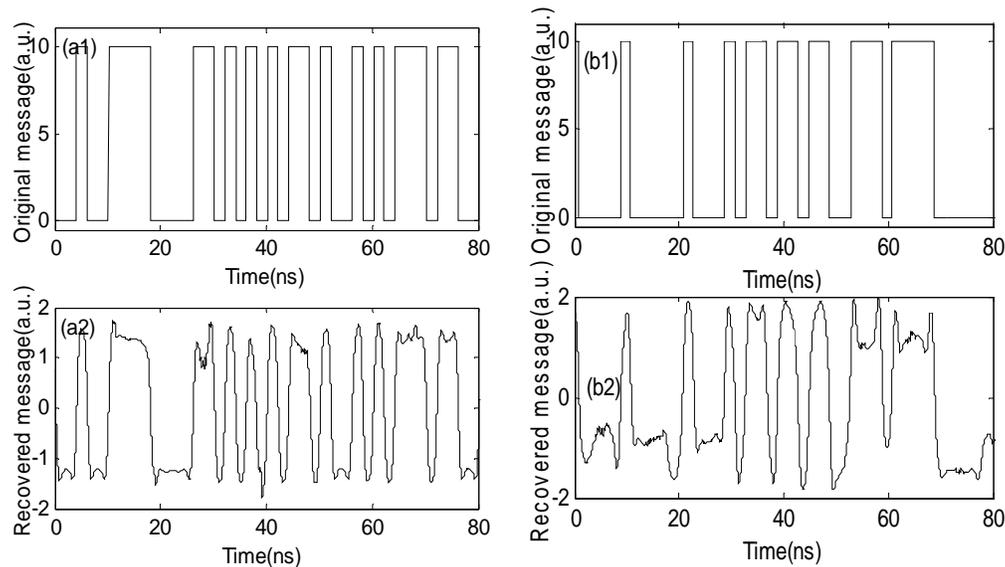


Fig. 4. Encoding and decoding message, where (a) and (b) correspond to open-loop and closed-loop, respectively.

4. Conclusions

In this paper, we have studied and compared the synchronization properties of two unidirectional coupled single mode semiconductor lasers subject to incoherent optical feedback under closed-loop and open-loop schemes. The results show that both schemes can achieve effective synchronization, where open-loop scheme is less sensitive to parameters mismatch than the closed-loop scheme. Furthermore, communication performances under the two schemes have been examined briefly, and a better performance of message decoding is observed for open-loop scheme than that for the closed-loop one.

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