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Simultaneously bidirectional transmission of message between three coupled semiconductor lasers

Qiliang Li [a], Shanshan Lu [a,*], Qi Bao [a], Dewang Chen [a], Miao Hu [a], Ran Zeng [a], Guowei Yang [a], Shuqin Li [b]

[a] Institute of Communication and Information Systems, College of Communication, Hangzhou Dianzi University, Hangzhou 310018, China
[b] College of Software Engineering, Tongji University, Shanghai 200092, China

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ABSTRACT

In this paper, we present a chaos-based scheme which allows for bidirectional transmission and recovery of message by simultaneously changing the feedback phase and coupling phase. In our scheme, three semiconductor lasers are mutually connected, and in each link the partially transparent mirror is used to supplement the degree of freedom to produce the chaotic carrier, moreover, the coupling between semiconductor laser 1, laser 2 and laser 3 through a partially transparent mirror induces the delay and chaos dynamics. We numerically have proven that three lasers can be fully in synchronization, and the message which is introduced by ON/OFF phase shift keying on the ends of each laser can be successfully encoded and decoded, at last the system can realize the bidirectional transmission of message between three parties.

1. Introduction

The study of chaotic systems has been received an extensive attention due to many applications, such as lidar, and coherence tomography, neural network, biology, economic and secure communication [1–5]. For a chaotic secure communication system, their attractive features of a chaotic carrier, in which a message is encoded and decoded, are their broadband spectrum and the possibility of synchronizing these chaotic waveforms [6]. The chaotic output of a transmitter acts as a carrier in which a message is encoded. Because the amplitude of the message is far less than the typical fluctuations of the chaotic carrier, thus it is very difficult to separate out the message from the chaotic carrier. When coupled chaotic systems are able to synchronize their output if the appropriate conditions are satisfied [7], a message is decoded. Concretely, in order to decode the message, the transmitted signal is coupled to the receiver which is highly similar to the transmitter. The receiver synchronizes with the chaotic carrier itself, thus the message can be recovered by monitoring the synchronization error between the receiver outputs and the transmitted signal. Therefore, the chaotic synchronization is the key to realize the whole system.

Chaos is deterministic random-like process in nonlinear systems, and it is aperiodic, bounded, and sensitive to initial conditions. Early, the chaotic systems would seem to be dynamics which defy synchronization, and the chaotic signal was not proposed to use to communication until Bateni et al. try to use the chaotic signal to the multiple-address digital communication system [8]. However, since Pecore and Carroll demonstrated in 1990 that a chaotic system can be synchronized with a separate chaotic system provided that the conditional Lyapunov exponents (CLE) of the drive and response systems are all negative [7], and proposed a novelty method about the effect of filtering on communication using synchronized chaotic circuits in 1996 [9], the chaotic communication has made rapid progress, and researchers do a lot of works in the aspect of trying to find various ways to realize the chaotic communication [6,10–16]. A field experiment performed in a metropolitan area network of the city of Athens (Greece) has confirmed the potential of this technique [10]. Very recently, chaotic semiconductor ring lasers (SRLs) have been the subject of numerous theoretical and experimental investigations duo to its applied interests. Vicente proposed a chaos-based communication scheme allowing for bidirectional exchange of information by coupling two semiconductor lasers through a partially transparent optical mirror in 2007 [6]. Ermakov studied synchronization of two unidirectional coupled semiconductor ring lasers working in a chaotic regime in 2013 [11], and the ON/OFF phase shift keying method is successfully applied to encrypt a message at a high bit rate. The other literatures still proposed several methods for encoding and decoding of a message within the chaotic carrier, which include chaos modulation, chaos shift keying, chaos masking, etc. [12–17].

* Corresponding author.
E-mail address: 162080104@hdu.edu.cn (S. Lu).

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Coupled semiconductor lasers (SL) have been found to be of considerable interests during the past ten years, mostly as instances for unidirectional and bidirectional message transmission between two SLs. In this work, we propose and numerically demonstrate a chaos-based bidirectional message transmission scheme which consists of three SLs. The distance between two neighbor SLs is the same, and three SLs are also nearly identical. In the numerical simulations, each SL is both the transmitter and the receiver, the mode of a SL is simultaneously sent to the other SLs. Thus when messages are encrypted using ON/OFF phase shift keying (OOPSK) on the ends of three SLs, these messages can be recovered by monitoring the synchronization error between the receiver outputs and the transmitted signal.

This paper is organized as follows: the theoretical framework is presented in Section 2. The dynamics of synchronization and robustness analysis are discussed in Section 3. Message transmission and recovery in the scheme with one transmitter and two receivers are analyzed in Section 4. Section 5 discuss and demonstrate a scheme allowing for trilateral message transmission and recovery by using OOPSK scheme. Section 6 is the conclusion.

2. Theoretical model

The close-loop schematic of a chaos-based bidirectional message transmission system is displayed in Fig. 1. It contains three chaotic SLs. Here three SLs are identical, and subject to delayed optical feedback, they are not only transmitter but receiver. In the OOPSK technique, the messages are codified by changing the feedback phase and the coupling phase at receiving end. and then they can be recovered (decrypted) by monitoring the synchronization error between the receiver outputs and the transmitted chaotic carrier. Six beam splitters (BS) are introduced to divide each output into two parts. One part is isolated into a photodetector (PD) to monitor the optical power of transmitter, and the other part is coupled into a phase modulator (PM) through coupler. The partial transparent mirrors (M) couple a part optical power of transmitter into receiving end, and reflect the other power into transmitter through a circulator.

The dynamical characteristics of three SLs are described by the well-known Lang–Kobayashi rate equations. According to Ref. [6], the set of equations for three SLs can be written as

$$\begin{aligned}\dot{E}_1 &= \mathrm{i}\Delta\omega_1 E_1 + \frac{1}{2}(1+i\alpha)\,G\left(N_1, \|E_1\|^2\right)E_1 + \kappa_{2,1}\exp\left(i\varphi_{2,1}\right)\\ &\quad\times E_2\left(t-\tau_1-\tau_2\right) + \kappa_{3,1}\exp\left(i\varphi_{3,1}\right)E_3\left(t-\tau_1-\tau_3\right)\\ &\quad+\kappa_{f,1}\exp\left(i\varphi_1\right)E_1\left(t-2\tau_1\right)\end{aligned} \tag{1}$$

$$\begin{aligned}\dot{E}_2 &= \mathrm{i}\Delta\omega_2 E_2 + \frac{1}{2}(1+i\alpha)\,G\left(N_2, \|E_2\|^2\right)E_2 + \kappa_{1,2}\exp\left(i\varphi_{1,2}\right)\\ &\quad\times E_1\left(t-\tau_2-\tau_1\right) + \kappa_{f,2}\exp\left(i\varphi_{m,2}\right)E_2\left(t-2\tau_2\right)\\ &\quad+\kappa_{3,2}\exp\left(i\varphi_{3,2}\right)E_3\left(t-\tau_2-\tau_3\right)\end{aligned} \tag{2}$$

$$\begin{aligned}\dot{E}_3 &= \mathrm{i}\Delta\omega_3 E_3 + \frac{1}{2}(1+i\alpha)\,G\left(N_3, \|E_3\|^2\right)E_3 + \kappa_{1,3}\exp\left(i\varphi_{1,3}\right)\\ &\quad\times E_1\left(t-\tau_1-\tau_3\right) + \kappa_{f,3}\exp\left(i\varphi_{m,3}\right)E_3\left(t-2\tau_3\right)\\ &\quad+\kappa_{2,3}\exp\left(i\varphi_{2,3}\right)E_2\left(t-\tau_2-\tau_3\right)\end{aligned} \tag{3}$$

$$\dot{N}_i = \frac{I_i}{e} - \gamma_e N_i - \left[G\left(N_i, \|E_i\|^2\right) + \gamma\right]\|E_i\|^2 \tag{4}$$

$$G\left(N_i, \|E_i\|^2\right) = \frac{g\left(N_i - N_0\right)}{1 + s\,\|E_i\|^2} - \gamma \tag{5}$$

Here $E_i(t)\,(i = 1,2,3)$ means the complex amplitude of optical field generated by laser i and the N_i means the carrier number, N_0 represents the transparent carrier number, $\|E_i\|^2$ represent the number of photons, $G\left(N_i, \|E_i\|^2\right)$ represents the gain function. κ, κ_f are the coupling coefficient and the feedback strength, respectively, $\varphi_1, \varphi_2, \varphi_3$ are the feedback phases, $\varphi_{i,j}(i \neq j)$ are the coupling phase. α is the line width enhancement factor, τ_1, τ_2 and τ_3 are coupling delay times, g is the differential gain, $I(= 2.2 \times I\mathrm{th})$ is the bias current, s is the saturation coefficient, γ and γ_e are the photon decay rate and the carrier decay rate, respectively.

Table 1
Parameter values used in our simulation.

Parameters	Symbol	Value
Delay time	$\tau_1\ \tau_2\ \tau_3$	1.4 ns
Threshold current	Ith	17.3 mA
Photon decay rate	γ	496 ns^{-1}
Carrier decay rate	γ_e	0.65 ns^{-1}
Differential gain	g	$1.2 \times 10^2\ \mathrm{ns}^{-1}$
Phases	φ	0
Line width enhancement factor	α	3
Transparent carrier number	N_0	1.25×10^8
Saturation coefficient	s	5×10^7
Feedback coefficients	κ_f	20 ns^{-1}
Couple coefficients	$\kappa_{i,j}$	20 ns^{-1}

In our model, only the adjacent lasers are mutually coupled through three partially transparent mirrors M_1, M_2, M_3 placed at the middle position in the pathway connecting both adjacent lasers, while the mirrors' transmittance on both sides are the same. Therefore, the light injected into the laser is the sum of the delay feedback and a part of adjacent laser through the mirror and the sum of the coefficients is equal to protect the existence of synchronization. The parameters like coupling coefficients and the feedback strength are chosen from the chaotic regime; we propose that the delay times of feedback and the couple are longer than the time of laser's relaxation oscillation.

We use the correlation coefficient to quantify the quality of chaos synchronization, which is defined as

$$P_{ij}(\Delta t) = \frac{\left\langle \left[E_i(t) - \langle E_i(t)\rangle\right] \cdot \left[E_j(t-\Delta t) - \left\langle E_j(t-\Delta t)\right\rangle\right]\right\rangle}{\sqrt{\left\langle \left|E_i(t) - \langle E_i(t)\rangle\right|^2\right\rangle \cdot \left\langle \left|E_j(t-\Delta t) - \left\langle E_j(t-\Delta t)\right\rangle\right|^2\right\rangle}}$$
$$(i, j = 1, 2, 3)\,, \tag{6}$$

where $\langle\cdot\rangle$ denotes time average, $P_{ij}(\Delta t)$ is the shifted correlation coefficient between two SLs.

3. Synchronicity and robustness analysis

In this section, we will analyze the synchronicity and robustness of three lasers. We first use the plots of attractor in phase space to confirm that the system can yields the chaotic signals, and then use the synchronization plots to illustrate the existence of synchronicity among three lasers. We also use the chaotic intensity-modulation by modifying the bias current of a laser among three lasers and the chaotic phase-modulation to study the synchronization robustness. According to the Ref. [6] and other literatures, we choose these parameters in our simulation, as shown in Table 1.

We assume that the initial photon number of SL1 and SL3 are the same but the photon number of LS2 is different. Numerically solving Eqs. (1)–(5) we plot the diagrams of temporal traces of the optical power of SL1, SL2 and SL3 in Fig. 2. We can find that the trace of each laser exhibits chaos in Fig. 2(a), and in Fig. 2(b), which correspond to the partial temporal traces of the optical power. In the absence of any external perturbation both lasers operate in a chaotic regime, we can see clearly that these temporal traces among three lasers are very similar.

In order to further analyze the synchronization between SL1, SL2 and SL3, we use the cross correlation to explain the synchronization of signals among three lasers. As shown in inset Fig. 3, we plot the cross-correlation function between the output powers P_1 and P_2. The cross-correlation function exhibits the maximum peak at a time lag that amounts to the difference between the coupling times of both lasers with the mirror $\Delta\tau = \tau_1 - \tau_2 = 0$, with a correlation coefficient of 1.