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Enhanced chaos synchronization and communication in cascade-coupled semiconductor ring lasers

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ABSTRACT

We numerically investigate the properties of chaos synchronization in a master–slave configuration consisting of a master semiconductor ring laser (SRL) with self-feedback or cross-feedback and a solitary SRL (slave). Different coupling schemes related to global injection and mode-selective injection are proposed and explored in our simulations. The numerical results demonstrate that among the studied coupling motifs the synchronization performance between the modes of the two chaotic SRLs is better when global injection scheme is employed. Furthermore, enhanced chaos synchronization and communication in three cascade-coupled SRLs via global injection are reported, where the time delay signature cannot be identified from the outputs of the three SRLs due to the proper selection of cross-feedback parameters of the master SRL.

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1. Introduction

In recent years, semiconductor ring lasers (SRLs) have received much more attention [1–6]. This type of semiconductor lasers have a special cavity, namely the well-known circular-geometry cavity that allows SRLs to output light in two counterpropagating directions referred to as the clockwise (CW)/counterclockwise (CCW) mode. Generally speaking, SRLs are fascinating due to their rich dynamics, especially they can operate in different regimes [2], such as bidirectional continuous wave operation, bidirectional operation with alternate oscillations, and unidirectional operation. Under specific operating conditions, one of these regimes is usually favored in the SRLs. As an example, unidirectional behavior (CW or CCW mode operation) is achieved at high pump currents; in the case the nonlinear gain imposes a strong mode selection. In particular, the unique feature of directional bistability is of great interest since it enables SRLs to be developed for many important applications, such as all-optical switching and all-optical memories [7–9], to name only a few. Besides, as SRLs do not require cleaved facets or mirrors to form the laser cavity, they are commonly fabricated in a compact-device structure. Therefore, SRLs are highly integrable and scalable, making them promising sources for key components in photonic integrated circuits.

Considerable effort has been devoted to the investigation of the nonlinear dynamics of SRLs, both in solitary and coupled SRL-based systems. These dynamics originate from the complex interactions between the two lasing modes, as well as some external perturbations. Recently, chaotic dynamics of semiconductor lasers have been successfully applied to secure communications [10–15] and fast physical random number generators [16,17]. Like other semiconductor lasers, the SRL allows weak or strong chaos generation under external perturbations, such as optical feedback [18], optical coupling and injection [19], and current modulation [20]. Among them, SRLs subject to optical feedback can output chaotic signals in large parameter regions when the feedback is extremely asymmetric [18]. Then numerical demonstration of chaos-based communications using chaotic SRLs has been reported, both in basic emitter/receiver [21] and broadcast-like [22] configurations. Also, fast

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random number generation has been achieved theoretically and experimentally using a single chaotic SRL even though the generated chaos bandwidth is relatively low [23]. These results demonstrate that SRLs can be feasibly applied to the above-mentioned applications as vertical-cavity surface-emitting lasers (VCSELs) and edge-emitting lasers (EELs) do. In addition to these features, SRLs exhibit other unique characteristics by combining external injection, and interactions between the two counterpropagating modes that include the nonlinear (gain saturation effect) and linear (backscattering) coupling. For example, it has been demonstrated that injection only one directional mode back into the counterpropagating mode leads to square wave oscillations [24]; time delay concealment, a key issue related to security, both in intensity and phase dynamics of SRLs with asymmetric cross-feedback has been confirmed, which is of paramount importance for chaotic optical communication [25]. Despite these successful demonstrations in the literature, different coupling schemes using chaotic SRLs deserve systematic investigations, including global and mode-selective injection, in order to gain more insight into the applications of coupled SRLs. A thorough study on cascaded synchronization and communication with three chaotic SRLs are also interesting due to the relay characteristics of the original message sent in the transmitter. Especially, such communication is implemented under the conditions that the relevant time delay cannot be extracted by analyzing the chaotic intensity output. All of these considerations motivate further studies.

In this paper, we focus our attention on the SRL-based system because of its remarkable features in improving the security of chaos-based communications, as well as in probably large-scale monolithic integration. Nevertheless, it should be noted that the bit rate of message transmission is relatively low due to the limited chaos bandwidth of the SRLs. In the first part, we systematically investigate the chaos synchronization properties of two chaotic SRLs with different coupling schemes. In the second part a numerical demonstration of chaos synchronization and communication of three cascade-coupled SRLs is presented; in this configuration, the security is greatly enhanced by combining the global injection and time delay concealment. Throughout our studies, global injection is regarded as the two modes of the master SRL are simultaneously injected into the two modes of the slave SRL, including parallel injection (CW1 to CW2 and CCW1 to CCW2, and here the numbers ‘1’ and ‘2’ stand for master and slave SRLs, respectively), as well as cross injection (CW1 to CCW2 and CCW1 to CW2); mode-selective injection is defined as only one mode of the master SRL is injected into one mode of the slave SRL, i.e., CW1 to CW2, CCW1 to CCW2, CW1 to CCW2 or CCW1 to CW2.

2. Different coupling schemes

Chaos synchronization can be achieved by injection a part of light intensity of one chaotic SRL into another one. However, it is not easy to make a quick conclusion to the synchronization properties since there exist two modes for each SRL. Therefore, to better understand this, different coupling schemes for two chaotic SRLs are presented in this section. A typical schematic of a solitary SRL device that is composed of a circular laser cavity is shown in Fig. 1(a). As mentioned above, such a cavity is capable of sustaining two counterpropagating modes, i.e., CW and CCW modes. For the sake of convenience, an equivalent model of the SRL is depicted in Fig. 1(b), where the thick grey (red in color version) line with double arrows represents the nonlinear and linear interaction between both modes.

In the following sections, a rate equation model that accounts for the dynamics of the SRL is used. Without loss of generality, we assume in this paper that the used SRLs operate in a single transverse and single longitudinal mode and can sustain two counterpropagating modes, which is consistent with the assumptions in the literature. The model consists of two equations accounting for two slowly varying envelopes of the counterpropagating fields E_{CW} and E_{CCW}, and a third equation for the carrier number N [19–25]:

$$\dot{E}_{CW} = \kappa(1 + i\alpha)[g_{CW}N - 1]E_{CW} - (k_d + ik_c)E_{CCW} + \sqrt{D}\xi_{CW}, \tag{1}$$

$$\dot{E}_{CCW} = \kappa(1 + i\alpha)[g_{CCW}N - 1]E_{CCW} - (k_d + ik_c)E_{CW} + \sqrt{D}\xi_{CCW}, \tag{2}$$

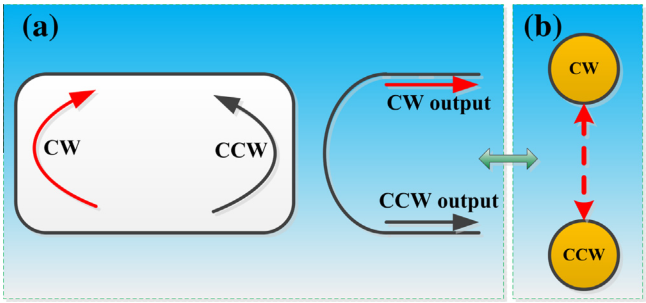

Fig. 1. Schematic of a solitary SRL (a) and its equivalent model (b). The directions of CW and CCW modes are depicted with grey curve (red in color version) and black curve, respectively. The think grey (red in color version) curve stands for the interaction between the two modes. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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