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Phase-modulated dual-path feedback for time delay signature suppression from intensity and phase chaos in semiconductor laser

Shuiying Xiang [a,*], Wei Pan [b], Liyue Zhang [b], Aijun Wen [a], Lei Shang [a], Huixing Zhang [a], Lin Lin [a]

[a] State Key Laboratory of Integrated Service Networks, Xidian University, Xi'an, Shaanxi 710071, China
[b] School of Information Science and Technology, Southwest Jiaotong University, Chengdu, Sichuan 610031, China

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ABSTRACT

Phase-modulated dual-path feedback (PM-DPF) is proposed to conceal time delay (TD) signatures from both intensity chaos and phase chaos in semiconductor lasers (SLs). The TD signatures are evaluated via both auto-correlation function and permutation entropy function. For the purpose of comparison, we also consider three other feedback configurations: SL with single-path feedback (SPF), SL with phase-modulated single-path feedback (PM-SPF), and SL with dual-path feedback (DPF). It is found that, for four feedback configurations, under the condition of strong feedback, successful TD concealment from both intensity and phase chaos can only be realized in SL with PM-DPF, due to the joint contribution of dual path feedback structure and phase modulation. Furthermore, to check the key factor contributing to TD concealment in SL with PM-DPF, the effects of feedback strength, feedback delay, modulation depth and modulation frequency are examined carefully. It is shown that, to obtain successful TD concealment from both intensity and phase chaos under the condition of strong feedback, the modulation frequency close to or greater than the relaxation oscillation frequency is suggested, while the modulation depth is the most important factor contributing to TD concealment, and higher modulation depth is desired. Besides, similar feedback strengths for two feedback paths are suggested. The TD signatures of intensity chaos for SLs with different feedback configurations are also verified experimentally. The SL with PM-DPF is an excellent chaotic source for security-enhanced chaotic communication systems as well as random number of generators based on chaotic SLs.

1. Introduction

Optical chaotic sources are promising candidates for potential applications such as secure optical communication systems [1–7] and high speed random number generators (RNGs) [8–14]. There have been increasing number of attractive chaotic sources reported in recent years, for example, conventional semiconductor lasers (SLs) [1–6], vertical-cavity surface-emitting lasers (VCSELs) [15–17], semiconductor ring lasers (SRLs) [13,18], optoelectronic oscillator (OEO) [19–22], fiber ring resonator [23], etc. For these chaotic sources, the delayed optical feedback and optical injection are commonly adopted approaches to obtain chaotic output. Note that, on one hand, the security of chaotic communication system and the randomness of RNG could be improved by increasing the unpredictability degree of chaotic signal, which can be realized by adopting strong feedback or injection. On the other hand, however, for large feedback strength or injection strength, the time delay (TD) signature of chaotic source will be extracted successfully via time series analysis techniques such as auto-correlation function (ACF) and delayed mutual information technique [24,25], which in turn threatens the security of chaotic communication system and reduces the randomness of RNG. That is to say, for chaotic source subject to conventional delayed optical feedback or injection, there is a tradeoff between the unpredictability degree and TD signature suppression. Two fundamental issues of chaotic source—the unpredictability degree of chaos and the TD signature of chaos—have attracted increasing attention, and have been extensively studied both experimentally and numerically [15–18,26–36].

Recently, to conceal the TD signature in SLs with optical feedback or optical injection, many effective schemes have been proposed and demonstrated [27–36]. For example, Wu et al. experimentally and numerically demonstrated that the TD signature could be suppressed from intensity chaos by adopting double optical feedback in SL [27]. Shahverdiev and Shore demonstrated that the TD signature could be eliminated from the laser output

* Correspondence to: State Key Laboratory of Integrated Service Networks, Xidian University, 2 South Taibai road, P.O. Box 119, Xi'an, Shannxi 710071, China. Tel./fax: +86 2988204468.
E-mail address: jxxsy@126.com (S. Xiang).

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autocorrelation in system with modulated opto-electronic feedback [28]. Zunino et al. adopted the permutation entropy (PE) and the permutation statistical complexity to discuss TD signature, and found that the PE was minimized and the permutation statistical complexity was maximized when the embedding delay of the symbolic reconstruction matched the feedback delay of the system [29]. Zhang et al. numerically predicted that the TD signature from intensity chaos could be erased by randomly phased-modulated optical feedback [30]. Besides, Li et al. numerically predicted that the TD signature suppression could be achieved in SL subject to distributed feedback from a fiber Bragg grating [34]. Note that, the majority works focused on the TD concealment from intensity chaos. However, Nguimdo et al. indicated that the TD signature concealed from the intensity time series could be retrieved successfully even using the same techniques based on the phase time series, which makes the TD concealment be more difficult [32]. In our previous work, we achieved TD signature suppression from both intensity and phase chaos in SL with dual-path injection [36]. However, it is still open and highly desirable to design an effective scheme to conceal TD signature from both intensity and phase chaos in SL subject to optical feedback, which is regarded as the most popular chaotic source, especially under the condition of strong feedback.

Remarkably, Bogris et al. proposed to employ a phase modulator (PM) inside the external cavity of a transmitter and authorized receiver lasers to apply phase variations for feedback lights, and demonstrated that the security was enhanced significantly [37]. Tronciu et al. numerically investigated the dynamics of SL with double cavity feedback, and demonstrated the effectiveness of chaotic communication based on on/off phase shift keying modulation, by varying the phase of the modulated feedback branch [38].

Motivated by these works, in this paper, we propose to adopt phase-modulated dual-path feedback (PM-DPF) in SL to suppress TD signatures from both intensity and phase chaos under the condition of strong feedback. For the purpose of comparison, we also consider SLs with three other feedback configurations: SL with single-path feedback (SPF), SL with phase-modulated single-path feedback (PM-SPF), and SL with dual-path feedback (DPF). The remainder of this paper is organized as follows. In Section 2, the theoretical models that describe the SLs with four feedback schemes are presented based on the Lang–Kobayashi (LK) equation [39]. In Section 3, the TD signatures of SLs with four feedback configurations are characterized in detail based on the ACF and PE functions. In particular, for SL with PM-DPF, the roles of feedback strength and feedback delay are discussed, and the effects of modulation depth and modulation frequency are also considered. In Section 4, the TD signatures of intensity chaos for SLs with different feedback configurations are also experimentally demonstrated. Finally, conclusions are drawn in Section 5.

2. Theory and model

The schematic diagram of SL subject to PM-DPF is shown in Fig. 1; the output of SL is injected into a PM, and a pseudorandom binary sequence (PRBS) generator is applied to the PM. The output of PM is then divided into two paths via an optical coupler (OC), and two fiber jumpers with different lengths are utilized to obtain two different feedback delays. Feedback strengths are adjusted via a variable attenuator (VA). The PM-DPF light is then fed back into SL via the optical circulator. Note that, when the devices in the dashed box are removed, the configuration of DPF is obtained. When the fiber jumper connected to VA1, i.e., the dashed line, is disconnected, the configuration of PM-SPF is realized. When both the fiber jumpers connected to VA1 and the devices in the dashed box are removed, the SL turns to subject to SPF. For convenience, we consider SL1 with SPF, SL2 with PM-SPF, SL3 with DPF, and SL4 with PM-DPF.

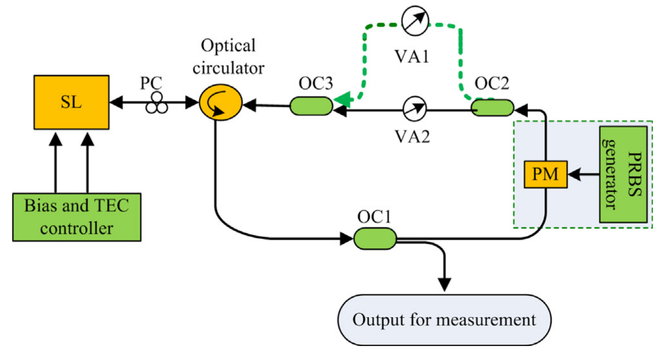

Fig. 1. Schematic diagram of SL subject to PM-DPF. SL is semiconductor laser, PM is phase modulator, VA1 and VA2 are two variable attenuators, PC is polarization controller, OC1, OC2 and OC3 are three optical couplers.

2.1. Rate equation models

The well-known LK equations are widely adopted to simulate the dynamics of SL with optical feedback [39]. For solitary SL, the rate equations for slowly varying amplitude of the electric field $E(t)$ and carrier number $N(t)$, assuming single-mode operation, can be expressed as [36,39]

$$\frac{dE(t)}{dt}=\frac{(1+i\alpha)}{2}\left[\frac{g[N(t)-N_0]}{1+s|E(t)|^2}-\frac{1}{\tau_p}\right]E(t) \tag{1}$$

$$\frac{dN(t)}{dt}=\frac{I}{q}-\frac{N(t)}{\tau_n}-\frac{g[N(t)-N_0]}{1+s|E(t)|^2}|E(t)|^2 \tag{2}$$

In our work, we consider four cases of feedback configurations; for SL1 with SPF, a feedback term should be added in Eq. (1) as follows [39]:

$$\frac{dE_1(t)}{dt}=\frac{(1+i\alpha)}{2}\left[\frac{g[N_1(t)-N_0]}{1+s|E_1(t)|^2}-\frac{1}{\tau_p}\right]E_1(t)+k_dE_1(t-\tau_d)\exp(-i\omega\tau_d) \tag{3}$$

where k_d and τ_d are feedback strength and feedback delay, respectively.

For SL2 with PM-SPF, the phase modulation process should be further considered in the feedback terms. The phase modulated light can be expressed as

$$E_p(t)=E_2(t)\times\exp[i\phi_{PM}(t)] \tag{4}$$

where $\phi_{PM}(t)$ is the phase variation resulted from the PM, which can be expressed as $\phi_{PM}(t)=\pi V_{RF}f_m(t)/V_\pi$, V_{RF} is voltage of the modulation signal applied to PM, $f_m(t)$ is the PRBS function with f being the modulation frequency, and V_π is the half-wave voltage of PM. We introduce $B=V_{RF}/V_\pi$ as the modulation depth. Hence, for SL2 with PM-SPF, Eq. (1) should be modified as

$$\frac{dE_2(t)}{dt}=\frac{(1+i\alpha)}{2}\left[\frac{g[N_2(t)-N_0]}{1+s|E_2(t)|^2}-\frac{1}{\tau_p}\right]E_2(t)+k_dE_2(t-\tau_d)\exp(-i\omega\tau_d)\exp[i\phi_{PM}(t)] \tag{5}$$

Similarly, for SL3 with DPF, two feedback terms should be added in Eq. (1) that can be read as

$$\frac{dE_3(t)}{dt}=\frac{(1+i\alpha)}{2}\left[\frac{g[N_3(t)-N_0]}{1+s|E_3(t)|^2}-\frac{1}{\tau_p}\right]E_3(t)+k_{d1}E_3(t-\tau_{d1})\exp(-i\omega\tau_{d1})+k_{d2}E_3(t-\tau_{d2})\exp(-i\omega\tau_{d2}) \tag{6}$$