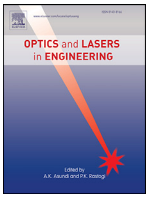
Optics and Lasers in Engineering 107 (2018) 342–351

Contents lists available at ScienceDirect

Optics and Lasers in Engineering

journal homepage: www.elsevier.com/locate/optlaseng



Simultaneous concealment of time delay signature in chaotic nanolaser with hybrid feedback

Amr Elsonbaty [a,b], Salem F. Hegazy [b,c], Salah S. A. Obayya [c,*]

[a] Department of Mathematics and Engineering Physics, Faculty of Engineering, Mansoura University, Mansoura 35516, Egypt
[b] National Institute of Laser Enhanced Sciences, Cairo University, Giza 12613, Egypt
[c] Centre for Photonics and Smart Materials, Zewail City of Science and Technology, Giza 12578, Egypt

ARTICLE INFO

Keywords:
Optical chaos
Optical feedback
Time delay (TD) signature suppression
Nanolasers

ABSTRACT

Simultaneous suppression of time delay (TD) signature in all observables of optical chaos emission, i.e. in both intensity and phase, has been achieved using two or more semiconductor laser (SL) sources or using two independent polarization components of single vertical cavity surface-emitting laser (VCSEL). In this paper, we examine for the first time the simultaneous TD feature suppression using a single nanolaser of single polarization state. The influence of hybrid optical/electrooptic feedback schemes employing either conventional, phase-conjugate, or grating mirror is evaluated. The concealment of TD signature is then investigated by means of the autocorrelation function. The results reveal the operational regions in each case with well eliminated TD signature in all observables. A secure communications system utilizing chaotic nanolaser is presented. Security analysis for a message transmitted in the form of a colored image is carried out which verifies the immunity of the system against possible statistical, brute force and differential attacks.

1. Introduction

Semiconductor laser (SL) sources have been considered the most common tool for generating optical chaos in the last two decades [1–6], compared with other laser sources such as gas lasers [7], solid-state lasers [8] and fiber lasers [9]. In fact, the fascinating features of optical chaos such as high sensitivity to initial states, random like behavior, broad bandwidth, and possibility of achieving chaos synchronization between master/slave systems make it distinguished in many promising applications. These potential applications include physical encryption, in both frequency and time domains, for information signals [2–4] and [10–13], physical ultra-fast random number generators [14–17], chaotic radar [18], chaotic lidar [19], optical time-domain reflectometry [20,21], and optoelectronic logic gates [22].

Generally, there are two approaches which can be counted for generation of optical chaos [23]. In the first type, the free running laser source exhibits chaotic output. The more recent example is quantum-dot vertical cavity surface-emitting laser (VCSEL) where polarization chaos is induced through nonlinear coupling between two elliptically polarized modes [24]. However, the low dimensional and narrow bandwidth chaos obtained from this type [25] represents a main issue. The second mechanism for generation of optical chaos relies on adding perturbations to laser system's parameters or state variables in the form of modulation [26], feedback or optical injection [27]. To enhance the security of chaos-based communication system, it is required to increase the complexity of chaotic attractor via employing high dimensional chaos generators. By incorporating the effects time delay (TD) on the laser system, high-dimensional optical chaos can be generated. This goal can be achieved via utilizing different types of all-optical [28–30] and electrooptic [31,32] feedbacks.

The main problem associated with the chaos-based encryption is that the high dimensionality of the chaos is not the unique factor that ensures the security of optical chaos cryptography [33], but also the prohibition of any crucial information related to the communication system from being extracted from the chaotic signal is essential. In other words, the SL internal parameters such as threshold current and wavelength along with external parameters e.g. the value of TD employed in optical chaos system are considered the primary secret keys. So, any eavesdropper who can spy out the TD signature is, at least theoretically, competent to reconstruct the chaotic system [34–37]. Another implication of existence of TD signature is diminishing of statistical performance of physical random bit generation [14] in addition to reduction of signal-to-noise ratio in chaotic radars [18].

Different designs of optical feedbacks are established to efficiently conceal TD signature in chaotic intensity series. Amongst them are optical feedbacks employing short-external-cavity regime [38], distributed feedbacks from a fiber Bragg grating [39], double optical feedbacks [40,41], double-cavity polarization-rotated optical feedback [6], and

---

[*] Corresponding author.
E-mail address: sobayya@zewailcity.edu.eg (S. S. A. Obayya).

https://doi.org/10.1016/j.optlaseng.2018.03.027
Received 31 January 2018; Received in revised form 25 February 2018; Accepted 22 March 2018
0143-8166/

three cascaded VCSELs [25]. However, Nguimdo et al. [42] revealed that TD information in the intensity time series which are confirmed to be entirely hidden can be easily obtainable via the phase time series. This breakthrough leaves realization of a system with fully suppressed TD signature in all observables more demanding.

There have been some experimental and theoretical investigations of simultaneous concealment of TD feature in both the intensity and phase of transmitted output. For example, in [43] Nguimdo et al. employed a configuration composed of cross-feedback semiconductor ring laser in order to achieve this goal. Further, it was verified that the optical chaos that induces from two SLs with dual-path injection [44] or from a cascaded scheme of three SLs [45] exhibits TD information suppression in both the intensity and phase of chaotic emission. More recently, it is shown that nonlinearly-modulated feedback in a ring of chaotic SL systems induces smaller TD signature in intensity and phase than that of the chaos induced by the conventional optical feedback [46].

However, multiple SLs are not the only approach for TD signature suppression in all observables. A single VCSEL can also lead to simultaneous TD signature suppression using electro-optic and optical feedbacks of incommensurable delays [47]. In this hybrid feedback scheme, the interference between two independent polarization components of VCSEL emission, subject to chaotic differential phase modulation, leads to an enhanced feedback signal suppressing simultaneously the TD signature in intensity and phase.

Nowadays, the integrated nanophotonic devices provide a plethora of subtle applications in optical communications and information processing. Nanolasers have received much interest due to its potential applications in system-on-a-chip technologies [48]. In fact, the nanolaser system shows an enhanced dynamical performance due to a combination of physical factors including the Purcell spontaneous emission enhancement factor and enhanced spontaneous emission coupling. Optical chaos can be generated in nanolasers either by optical injection, conventional or phase conjugate optical feedbacks [48–50]. However, the limitations in size, complexity, and power consumption in a nanophotonic chaos chip renders the use of single nanolaser highly desirable. We therefore come to the not-yet-explored question: “can a single nanolaser emitting a beam of a well-defined polarization produce optical chaos with simultaneous TD signature suppression?”

In this paper, we attempt to answer that question. We first investigate the occurrence of TD feature in chaotic nanolasers exposed to different types of optical feedbacks. In particular, the cases where conventional, phase conjugate, and grating mirror feedbacks are considered. Second, we present a hybrid all-optical/electro-optic feedback scheme and assess its role in TD suppression in all observables. As an application, secure communications system based on a single nanolaser is proposed. The immunity of the presented encryption scheme is assessed against possible statistical, brute force and differential attacks.

The rest of the paper is organized as follows: The effects of different types of external optical feedback is examined in Section 2. The proposed schemes for TD suppression and secure communications are included in Section 3 and Section 4, respectively. Section 5 contains the conclusion.

2. Effects of external optical feedback

It is known that the difficulty of extracting TD information directly from time series results from the complexity of chaotic attractor, so that the existence of TD feature in each case is investigated via statistical means. Among the several statistical techniques which are suitable to quantitatively identify the TD signature in chaotic time series is the autocorrelation function (ACF). This technique has the advantage of being computationally efficient, robust, and immune to white noise [43,51]. The ACF can precisely measure how much a given time series waveform matches its time-shifted version such that the locations of peaks in ACF curve illustrate the presence of TD signature in chaotic output.

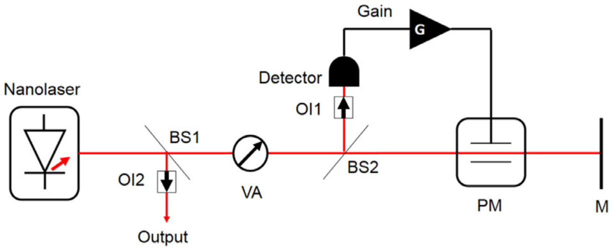


Fig. 1. Schematic of the proposed setup. The nanolaser emission is first subjected to a beam splitter (BS1) then a variable attenuator (VA). The attenuated beam passes the second beam splitter (BS2) which splits it between an electrooptic feedback circuit of gain G and an optical feedback with a phase modulated by a delayed version of the optical intensity. This hybrid-feedback arrangement merges both chaos effects owing to the delay of the optical feedback as well as the delay of electrooptic feedback circuit. The mirror M can be either a conventional mirror (CM), a phase-conjugate mirror (PCM), or a grating mirror (GM). PM and OI denote phase modulator and optical isolator, respectively.

Here, the ACF for chaotic intensity and phase time series is defined as follows

$$\mathrm{C}(\Delta t) = \frac{[\rho(t+\Delta t) - \langle \rho(t+\Delta t)\rangle][\rho(t) - \langle \rho(t)\rangle]}{\langle [\rho(t+\Delta t) - \langle \rho(t+\Delta t)\rangle]^2\rangle^{\frac{1}{2}} \, \langle [\rho(t) - \langle \rho(t)\rangle]^2\rangle^{\frac{1}{2}}}, \tag{1}$$

where $\rho(t)$ is either the intensity $I(t)$ or the phase $\varphi(t)$, $\langle\rangle$ denotes the average of time series, and Δt is the time lag which is taken at 25 ps steps in numerical simulations. Now, let’s define m as being a mismatch coefficient and assume that $\tilde{\tau}$ is the round trip time to be extracted. Therefore, if the modulus of ACF value in neighborhood of $\tilde{\tau}$ has obviously larger value compared with contemporary values in other intervals, it reveals the existence of TD signature. To quantify the weakness or strength of TD signature mathematically, a good measure is then the peak signal to mean ratio (PSMR) which is determined as $\mathrm{Max}\ \{|\mathrm{C}(\Delta t)|\}/\ \mathrm{C}(\Delta t)$, where $\Delta t \in [\tilde{\tau}(1-m), \tilde{\tau}(1+m)]$. Because the PSMR values of the intensity and phase time series can equally be used to unveil the time delay information, both PSMRs are combined in one variable, denoted as *combined PSMR*. It is reported that TD features are well suppressed when the value of PSMR is less than 4 [47].

Fig. 1 depicts the schematic diagram of the proposed setup. Following is the mathematical model for nanolaser subject solely to external optical feedback (i.e., electrooptic gain $G = 0$) employing conventional mirror (CM), phase conjugate mirror (PCM) or a grating mirror (GM).

2.1. CM optical feedback

Let $I(t)$, $\varphi(t)$ and $N(t)$ denote the photon density, the phase and the carrier density, respectively, all at the time t. The rate equations describe a single semiconductor metal clad nanolaser in this case are expressed as [50]

$$\begin{aligned}\frac{dI(t)}{dt} &= \gamma\left(\frac{F\beta N(t)}{\tau_n} + \frac{g_n\big(N(t)-N_0\big)}{1+\epsilon I(t)} I(t)\right) - \frac{1}{\tau_p} I(t) \\ &\quad + 2k\sqrt{I(t)I(t-\tau)}\cos(\omega_0\tau + \varphi(t) - \varphi(t-\tau)),\end{aligned} \tag{2}$$

$$\begin{aligned}\frac{d\varphi(t)}{dt} &= \frac{\alpha}{2}\gamma g_n(N(t)-N_{th}) \\ &\quad - k\sqrt{\frac{I(t-\tau)}{I(t)}}\sin(\omega_0\tau + \varphi(t) - \varphi(t-\tau)),\end{aligned} \tag{3}$$

$$\frac{dN(t)}{dt} = \frac{J_{dc}}{eV_a} - \frac{N(t)}{\tau_n}(F\beta + 1 - \beta) - \frac{g_n(N(t)-N_0)}{1+\epsilon I(t)} I(t), \tag{4}$$

where the rate at which a proportion of laser field is reflected back from the mirror into the nanolaser active region is defined as the feedback