CHAOS BASED COMMUNICATIONS USING ON-OFF SHIFT KEYING METHOD

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Abstract

We discuss the dynamical behavior of a single mode semiconductor laser under the influence of multiple optical feedbacks. It is shown that the system displays, under certain conditions, chaotic behaviors appropriate for chaos based communications. The synchronization of two unidirectional coupled (master-slave) systems is also studied. Finally, the conditions for message encoding by using the on/off phase shift keying encryption method are identified and examples of message encoding/decoding are presented.

1. Introduction

The phenomenon of synchronization has been the subject of numerous theoretical and experimental investigations in many research areas [1]. In particular, synchronised chaotic waveforms have found applications in chaos based communication systems. Different setups for chaotic data transmission have been proposed in literature [2-7]. From the application point of view, chaos based communications have become an option to improve privacy and security in data transmission, especially after the recent field demonstration on the metropolitan fiber networks of Athens [8]. In optical chaos based communications the chaotic waveform is usually generated by using semiconductor lasers subject to either all-optical [9-13] or electro-optical [14-16] feedback. Configurations using Fabry-Perot resonators providing the optical feedback, the so called frequency selective feedback, have been also studied [17-19]. In this case the feedback can either destabilize the laser emission or improve the stability of the CW emission allowing the control of the laser in a non-invasive way [17]. Recently, the chaos modulation technique has been successfully applied to an integrated device composed of a semiconductor laser and a double cavity that provides optical feedback [20]. One of the most attractive schemes in terms of security is the on/off phase shift keying (OOPSK) encryption method [21-23] where the codification is achieved by slightly modulating the phase of the optical feedback of the emitter. The physical basis for OOPSK is that the synchronization behavior of the receiver acts as a sensitive detector for variations of the transmitter feedback phase: suitable discrete changes yield the dynamics of the receiver to jump between synchronized and de-synchronized states. In contrast to these drastic changes in the receiver dynamics, changes in the emitter dynamics should not be noticeable neither in the intensity dynamics nor in the RF or optical spectra. The principle of the OOPSK encryption works as follows. The message is encoded by switching between two states of the master system that yield highly correlated (synchronized) states (Bit “0”) or less correlated (desynchronized) states (Bit "1") in the receiver system. Hence, the message can be simply recovered by monitoring the synchronization error. The controlled variations in the master system can be accomplished by inserting, e.g., an electrooptical modulator within the external cavity of the transmitter. The message is decoded by detecting whether the receiver synchronizes or not with the input carrier [23].

The paper is structured as follows. We start in Section 2 by describing the model for the investigated scheme. Section 3 presents a study of the dynamics of a laser under the influence of a multiple feedbacks. In Section 4 the OOPSK encryption method is demonstrated. Finally, the summary and conclusions are given in Section 5.

2. Model and equations

The proposed setup is depicted schematically in Fig. 1. It consists of a semiconductor laser coupled to multiple cavities. In the model we only account for single reflexion in each cavity.

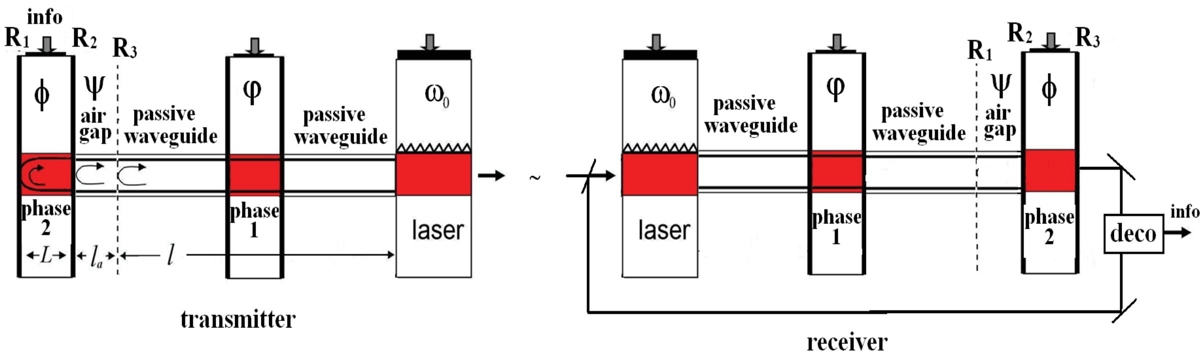

Fig. 1. A sketch of the proposed setup for chaos synchronization and message encoding, using semiconductor lasers under the influence of multiple feedbacks. R_1, R_2 and R_3 are reflectivities. The lengths of the external cavities are: l = 4 cm, l_a=5 µm, $L=250\ \mu m$. ω_0 is the free running frequency of the CW laser.

In the present study, the laser dynamics is analyzed in the framework of the extended Lang-Kobayashi equations for the complex field amplitude E and an excess carrier density N [24]

$$\frac{dE_{t,r}}{dt}=(1+i\alpha)\left[\frac{g(N_{t,r}-N_0)}{1+s|E_{t,r}|^2}-\frac{1}{\tau_{ph}}\right]\frac{E_{t,r}}{2}+\gamma_1 e^{i\varphi}E_{t,r}(t-\tau_1)+\gamma_2 e^{i\psi}E_{t,r}(t-\tau_2)+\gamma_3 e^{i\phi}E_{t,r}(t-\tau_3)+k_r E_t \quad (1)$$

$$\frac{dN_{t,r}}{dt}=\frac{I_{t,r}}{e}-\frac{1}{\tau_e}N_{t,r}-\frac{g(N_{t,r}-N_0)}{1+s|E_{t,r}|^2}|E_{t,r}|^2 \quad (2)$$

The subscripts t and r refer to transmitter and receiver lasers, respectively. The last term in equation (1) is present only in receiver laser and describes the unidirectional coupling between transmitter and receiver. k_r is the coupling strength given by $\kappa_r=\sqrt{1-R}\eta_{ext}/\left(\tau_c\sqrt{R}\right)$ where R is facet power reflectivity of the slave laser (R=30%), τ_c is the cavity roundtrip time of the light within the laser $(\tau_c=10ps)$, η_{ext} accounts for losses different than those introduced by the laser facet $(\eta_{ext}=0.5)$ resulting in $\kappa=75ns^{-1}$. τ_1, τ_2 and τ_3 are roundtrip. γ_1, γ_2 and γ_3 are the feedback strengths governed by the reflectivities R_1, R_2 and R_3, respectively. $\varphi=\omega_0\tau_1$, $\psi=\omega_0\tau_2$ and $\phi=\omega_0\tau_3$ are the accumulated optical phases, which, without loss of generality, can be assumed to take values between 0 and 2π. The other parameter values are: $\alpha = 5$ the linewidth enhancement factor; $g = 3.55 \cdot 10^{-8} ps^{-1}$ the differential gain parameter, $s = 4 \times 10^{-7}$ the gain saturation coefficient, $\tau_{ph} = 3ps$ and $\tau_e = 1.85ps$ the photon and carrier lifetimes, respectively and $N_0=1.1x10^8$ the carrier number at the transparency. These parameters, that are considered identical for both lasers, are used for the calculated results shown in all figures in the paper. The injection current is fixed at $I=25mA$ ($I_{th}=10.5$ mA).

3. Transmitter laser dynamics

This section concerns the behavior of a semiconductor laser under the influence of a multiple feedbacks. For small enough feedback strengths semiconductor lasers under the influence feedback show CW or pulsating operations. Chaotic behavior appears if the feedback strength is increased enough. It is well known that the autocorrelation time is related to the complexity of the generated chaos. The shorter the correlation time is the more chaotic and less predictable the dynamics is. Figure 2 shows the calculated autocorrelation time [25] for laser under the influence of multiple feedbacks in the $(\phi - \varphi)$ plane. The darker regions correspond to the lower autocorrelation time. It can be clearly seen how the autocorrelation time changes in the plane of the two parameters and, in particular, how for fixed phases the autocorrelation time becomes much shorter providing conditions for chaos based communications.

We next examine the laser dynamics in terms of bifurcation diagrams. Figure 3 displays bifurcation diagrams of a semiconductor laser under the influence of multiple feedbacks for different phases acting as a bifurcation parameter. For each value of the feedback strength the figure displays the values of the maxima of the time traces of the emitted power. It is well known that as the feedback strength is increased a scenario compatible with quasiperiodic route to chaos appears. Figure 4 displays the bifurcation diagrams of a semiconductor laser subject to multiple feedbacks when the feedback phase φ (a) and ϕ (b) are acting as bifurcation parameters for different values of feedback phase ψ. It can be noticed from these figures that the fully developed chaotic dynamics is found for any value of phases.

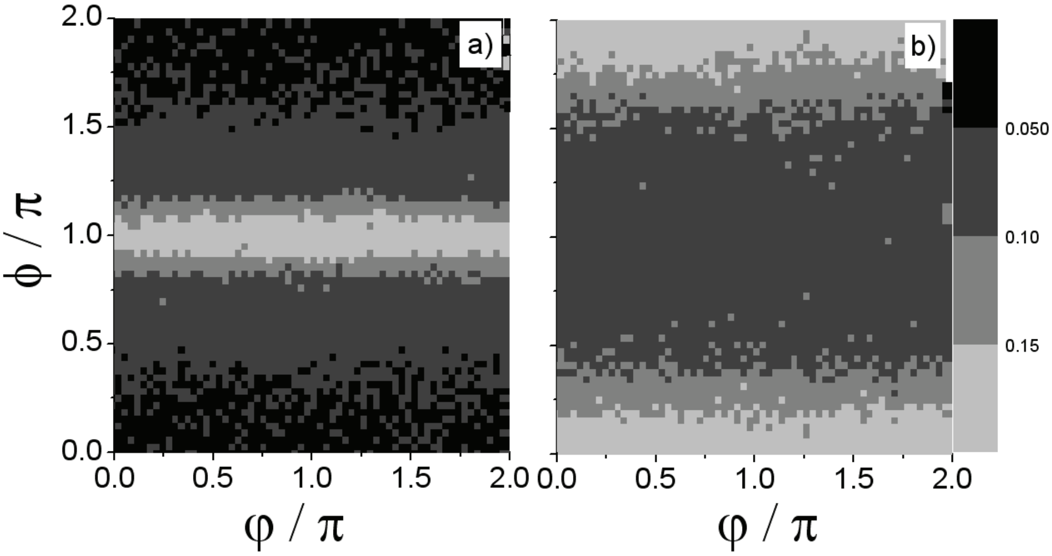

Fig. 2. The autocorrelation time as a function of phases φ and ϕ for (a) $\psi = 0$ and (b) $\psi = \pi$. Other parameters are $\gamma_1 = 15ns^{-1}$, $\gamma_2 = 10ns^{-1}$, $\gamma_3 = 15ns^{-1}$.

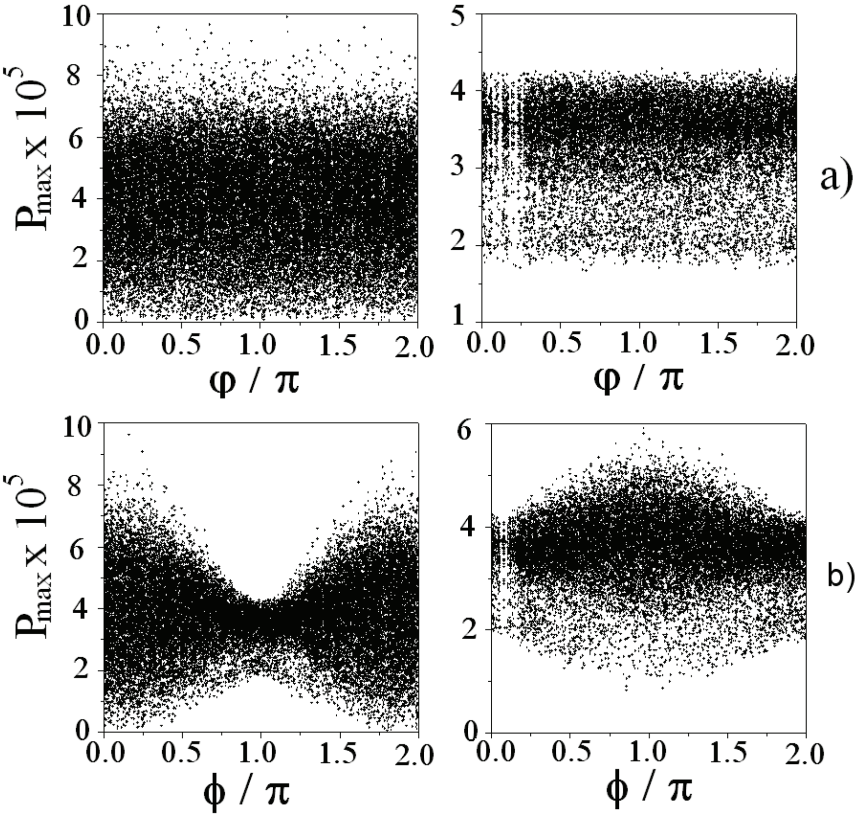

Fig. 3. Bifurcation diagram of the output power for a) the phase φ as bifurcation parameter for φ=0 and ψ=0 (left), ψ=π (right); b) the phase ϕ as bifurcation parameter for ϕ=0 and ψ=0 (left), ψ=π (right). The other parameters are $\gamma_1 = 15ns^{-1}$, $\gamma_2 = 10ns^{-1}$, and $\gamma_3 = 15ns^{-1}$. Each dot represents a peak of the output power.

4. Synchronization and message transmission

So far we have clarified different aspects of the transmitter laser dynamics under a DCF. In what follows we focus on the transmitter–receiver configuration and evaluate the synchronization properties. One important characteristic of OOPSK encryption is the resynchronization time, i.e., the time required by the setup to synchronize when the link between master and slave lasers is interrupted. We estimated the resynchronization time for different values of phases. In fact, we have found that under certain phases we can achieve the resynchronization time of few ns.

Now we consider the influence of a mismatch between the phases ϕ_s of the slave laser with respect to that ϕ_m of the master laser on the cross correlation coefficient. Figure 4 shows the values of this coefficient in the plane $(\phi_s - \phi_m)$ for feedback strengths $\gamma_1 = 15ns^{-1}$, $\gamma_2 = 10ns^{-1}$, and $\gamma_3 = 15ns^{-1}$ and the coupling coefficient $\kappa_r = 75ns^{-1}$. Other parameters are identical for the master and slave lasers. It can be clearly seen that highest correlation coefficients are achieved in a certain region when the two phases coincide, i.e., $\phi_m = \phi_s$ while the correlation degrades when the phases start to be different. Points A and B in Fig. 4 correspond to the operating points that will be considered later for message encoding and decoding using OOPSK encryption. The point A is chosen to have high correlation while the point B corresponds to a state with low correlation.

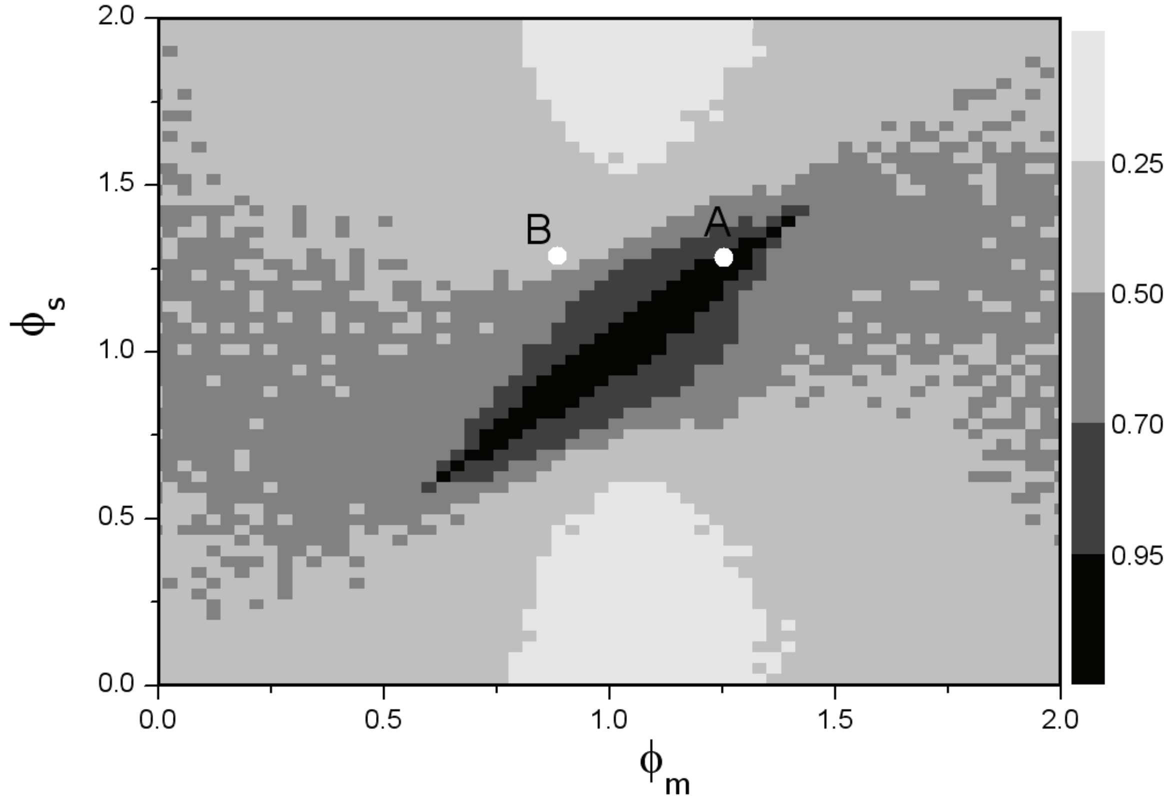

Fig. 4. Cross correlation coefficient in the $(\phi_s - \phi_m)$ phase space. The other parameters are $\gamma_1 = 15ns^{-1}$, $\gamma_2 = 10ns^{-1}$ $\gamma_3 = 15ns^{-1}$, $\kappa_r = 75ns^{-1}$, $\varphi_m = \varphi_S = 0$, $\psi_m = \psi_S = 0$ high degree of synchronization is characterized by light grey level. Phases are varied in steps of 0.05 radians.

In the OOPSK technique the message is codified by changing the feedback phase of the master laser without introducing significant changes in the time trace or spectrum of the emitted light [22, 23]. In this setup the slave laser for which the feedback phase is kept constant, acts as a detector of the synchronization quality. When the feedback phases of the emitter and receiver coincide the correlation between the outputs of the two systems is high while it is low when the phases are different. Figure 5 depicts the process of 0.25 Gbit/s message OOPSK encryption. On the top panel the digital message is shown. Figure 5b shows the synchronization error when the phase of the receiver laser is changed from point A (bit "0") to point B (bit "1") of Figure 4. Figure 5c shows the chaotic carrier with message. Figure 5d shows that the message can be successfully recovered after a standard filtering process. Thus, the proposed setup can distinctly increase the bit rate compared with that previously obtained in [23].

5. Summary and conclusions

We have carried out an investigation of the dynamics of a semiconductor laser under the influence of multiple feedbacks. The results presented in this paper show that under appropriate conditions such a laser is capable of generating a robust chaotic behaviour. It has been shown that two of these devices can be synchronized when operating in the chaotic regime in a master-slave configuration if some parameters are properly matched. Finally, OOPSK encryption method can be successfully applied at a rate of hundreds of Mbit/s.

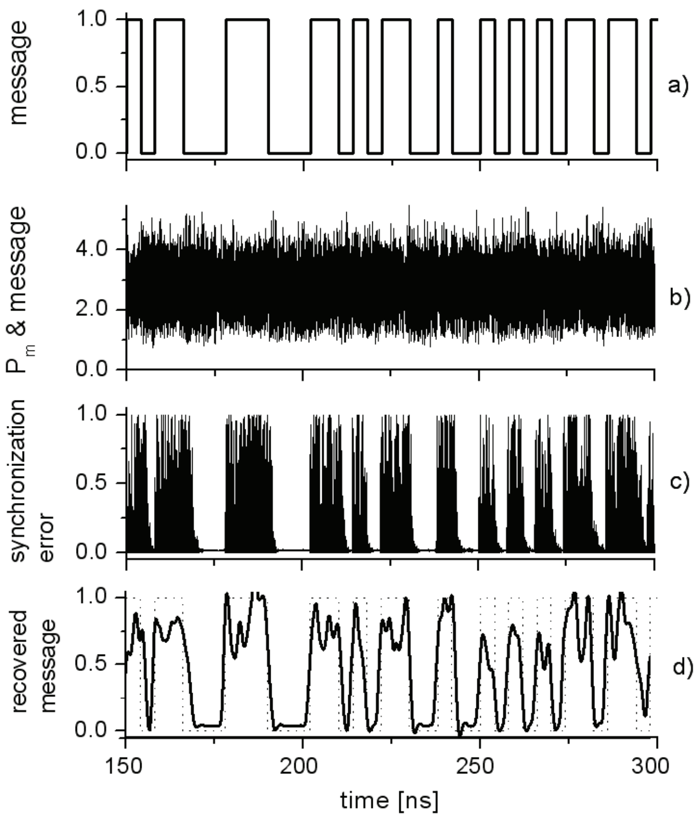

Fig. 5. On/off phase shift keying encoding and decoding of 0.25 Gb/s digital message. a) Encoded message. b) Output of the master laser with a message c) decoded message represented by the synchronization error. d) Recovered message after filtering. The other parameters are the same as in Fig. 4.

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