On/Off phase shift keying encryption method of semiconductor lasers with an air gap

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***Abstract* — We discuss the dynamical behaviour of a single mode semiconductor laser with an air gap under the influence of multiple optical feedbacks. It is shown that the system displays, under certain conditions, chaotic behaviours 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.**

***Index Terms* — chaos based communications, semiconductor lasers with an air gap**

I. INTRODUCTION

During recent years the phenomenon of synchronization has opened the new way to investigate and apply the chaos to communication systems [1-4]. Different setups for chaotic data transmission have been proposed in the literature [5-9]. Mach progress was made since Pecora and Carroll [5,6], have shown theoretically and experimentally that two chaotic systems can be synchronized. These papers brought together two fields chaos theories and communications, and have opened a new research area in communications using chaos. From the application point of view, chaos based communications has become an option to improve privacy and security in data transmission. In optical chaos based communications the chaotic waveform is usually generated by using semiconductor lasers subject to either all-optical [10-12] or electro-optical [13,14] feedback. Recently, configurations using multiple optical feedback loops have also been studied both in theory and experiment [15-17]. The chaos modulation technique has been successfully applied to an integrated device composed of a semiconductor laser subject to multiple optical feedback loops [17].

However, one of the most attractive schemes in terms of security is the on/off phase shift keying (OOPSK) encryption method [18,19] 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 behaviour 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 message is decoded by detecting whether the receiver synchronizes or not with the input carrier.

In this paper we report studies on OOPSK encryption method applied to semiconductor laser with air gap subject to multiple feedbacks. 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. The OOPSK encryption method is demonstrated. Finally, the summary and conclusions are given in Section 4.

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II. LASER SETUP AND EQUATIONS

The proposed setup is depicted schematically in Figure 1. It consists of a semiconductor DFB laser coupled to multiple cavities one being air gap. In the model we only account for single reflexion in each cavity. The cavity phases φ and ϕ can be controlled independently by supplied currents, while the phase ψ is fixed due to the cutting process. The reflection between air gap and both waveguide and phase sections is 0.3.

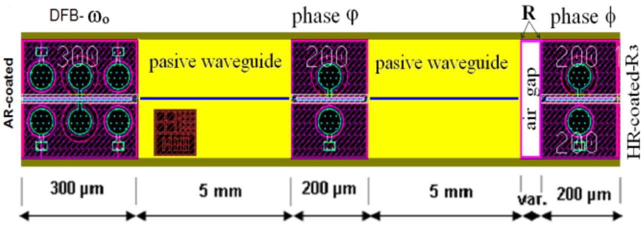

Figure 1 A sketch of the multi-section laser setup for chaos synchronization and message encoding (for more details see [20,17]). R_1 =R$_2$ =R and R_3 are reflectivities. The length of the air gap is l_a=2 µm, ω_0 is the free running frequency of the CW laser.

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 [21]

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

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

The subscripts *t* and *r* refer to transmitter and receiver lasers, respectively. The last term in the equation (1) is present only in receiver laser and describes the unidirectional coupling between transmitter and receiver. κ_r is the coupling strength given by $\kappa_r = \sqrt{1-R_s}\,\eta_{ext}/(\tau_c\sqrt{R_s})$, where R_s is facet power reflectivity of the slave laser (R_s=30%), τ_c is the cavity roundtrip time of the light within the laser τ_c=10 ps, η_{ext} accounts for losses different than those introduced by the laser facet (η_{ext}=0.6) resulting in κ = 90 ns^{-1}. τ_1, τ_2 and τ_3 are roundtrips. 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: α = 5 the linewidth enhancement factor; g = 1.50·10^{-8} ps^{-1} the differential gain parameter, s = 4·10^{-7} the gain saturation coefficient, τ_{ph} = 3 ps and τ_e = 2 ns the photon and carrier lifetimes, respectively and N_0=1.2x10^8 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=40 mA (I_{th}=11.4 mA). specified.

III. TRESULTS AND DISCUSSION

We begin our analysis by studying the behavior of a semiconductor laser under the influence of a multiple feedbacks. It is well known that for small enough feedback strengths semiconductor lasers under the influence of feedback show CW or pulsating operations. Chaotic behavior appears if the feedback strength is increased enough. Fig. 2 illustrates typical time traces (left) and the power spectra (right) of a semiconductor laser under the influence of multiple feedbacks in the chaotic regime.

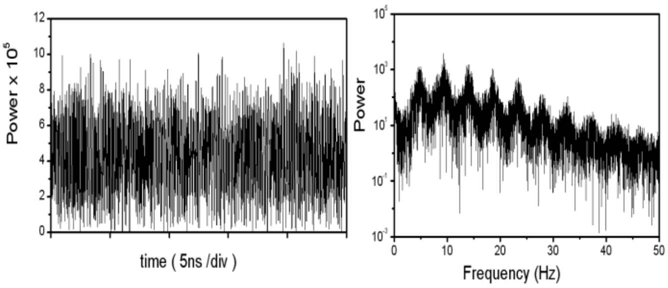

Figure 2 Numerical results: pulse trace of optical power (left) and optical spectra (right) of a semiconductor laser under the influence of multiple feedbacks for γ_1 = 15 ns^{-1}, γ_2 =10 ns^{-1}, γ_3 = 20 ns^{-1}, $\varphi = \pi/2$, $\psi = \pi/4$ and ϕ = 0.

It can be observed that the multiple feedbacks makes the laser behavior more complex compared with that of COF with a single mirror placed at the back laser facet see e.g. [16,17]. This fact was further confirmed by calculation of the autocorrelation time from eqs. (3) and (4) of [22]. These calculations yield to T_{ac}= 0.057 ns that is smaller than that of COF. Moreover, larger amplitude fluctuations when compared with COF can be observed. For more detail on behavior of a semiconductor laser with air gap see [17].

Figure 3 shows the experimentally measured pulse trace and optical spectra of a semiconductor laser with a 2μm air gap under the influence of multiple feedbacks for an injected current of 40 mA. These characteristics show a well established chaotic behaviour with a wide optical spectrum that agree very well with numerical results shown in Figure 2.

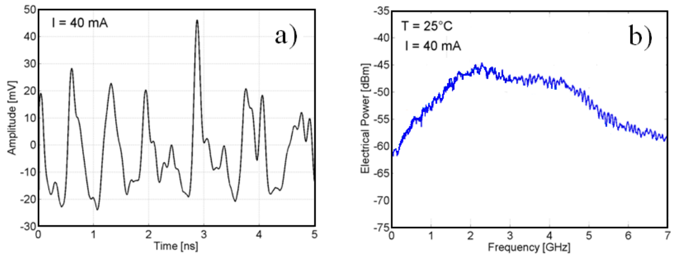

Figure 3 Experimental results: a) pulse trace and b) optical spectrum.

In the following we examine the laser dynamics in terms of bifurcation diagrams. It is well known that in semiconductor lasers with feedback when the feedback strength is increased several instabilities takes place. For low values of the feedback strength CW operation is observed. As the feedback strength is increased a scenario compatible with quasiperiodic route to chaos is obtained [see e.g. 15-17].

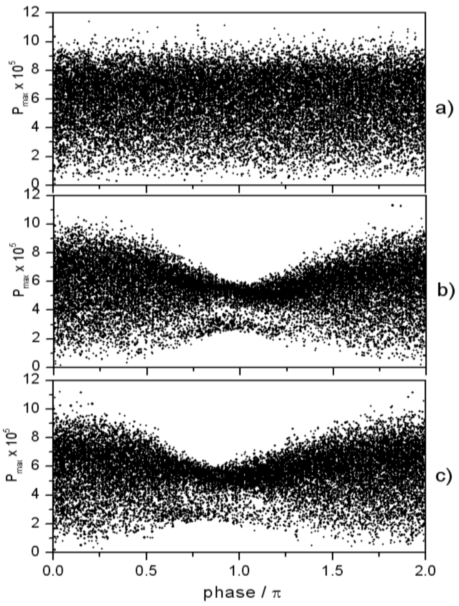

Figure 4 Bifurcation diagram of the output power for different phases as bifurcation parameters: a) phase φ - bifurcation parameter and $\psi = \pi/4$, ϕ = 0; b) phase ψ - bifurcation parameter and $\varphi = \pi/4$, ϕ = 0; c) phase ϕ - bifurcation parameter and $\varphi = \pi/2$, $\psi = \pi/4$. The other parameters are γ_1 = 20 ns^{-1}, γ_2 =15 ns^{-1}, γ_3 = 18 ns^{-1}. Each dot represents a peak of the output power.

We chose suitable values of feedback strength to achieve the chaotic behaviour. The phases φ, ψ, and ϕ remain the main parameters to be varied. Figure 4 displays bifurcation diagrams of a semiconductor laser under the influence of multiple feedbacks for different phases acting as a bifurcation parameter. In real device the phases φ and ϕ can be controlled by injected current in the phase section, while the phase ψ is fixed and determined by cutting process. For each value of the feedback strength the figure displays the values of the maxima of the time traces of the emitted power. Figure 4a shows a fully developed chaotic behaviour for any value of air gap cavity phase ψ. In addition, we mention that the numerical calculations show that in this parameter region any combination of phases φ, ψ and ϕ the laser behavior is chaotic. However, within small region close to ψ ~ ϕ ~ π chaotic behaviours with small amplitude become possible.

So far we have clarified different aspects of the single transmitter laser dynamics under the influence of multiple feedbacks. Now we focus on the transmitter–receiver configuration shown in Fig.5. As mentioned above several ways for encoding and decoding a message within the chaotic carrier has been proposed in the literature, including chaos modulation, chaos shift keying, chaos masking, etc. It has been suggested previously [15] that the OOPSK encryption method can ensure higher security of information transmitted compared with other methods.

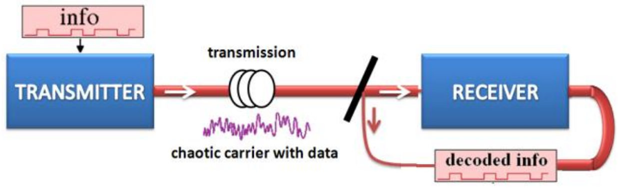

Figure 5 On/off phase shift keying encryption technique.

One important characteristic of OOPSK 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 and have found that under certain phases we can achieve the resynchronization time of few ns. It is known that the existence of a small resynchronization time is the requirement for an increase of transmitted bit rate. Finally, we have to find 2 operating points that will be consider for message encoding and decoding. Thus, 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 6 shows the values of this coefficient in the plane (ϕ_s -ϕ_m) for the coupling coefficient κ_r = 90 ns^{-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., $\phi_s = \phi_m$ while the correlation degrades when the phases start to be different. Points A and B in Figure 6 correspond to the operating points that will be consider 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. We choose the points A and B far from the region with chaotic behaviour with low amplitudes to ensure high complexity of chaos.

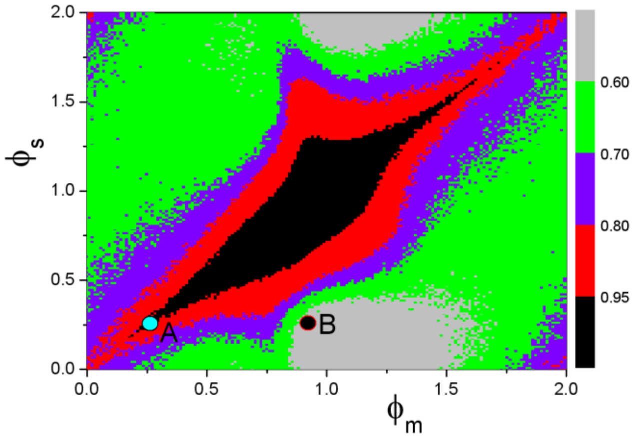

Figure 6 (online colour) Cross correlation coefficient in the (ϕ_s -ϕ_m) phase space. The other parameters are γ_1 = 20 ns^{-1}, γ_2 =15 ns^{-1}, γ_3 = 18 ns^{-1}, κ_r = 90 ns^{-1}, $\varphi_m=\varphi_s= \pi / 2$, $\psi_m=\psi_s= \pi / 4$. High degree of synchronization is characterized by black level.

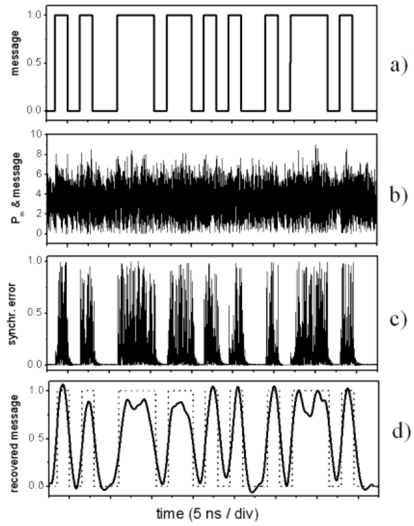

Figure 7 On/off phase shift keying encoding and decoding of 0.35 Gb/s digital message. a) Encoded message. b) Output of the master laser with a message c) decoded message represented by the synchronization error. d) Recovered message after filtering. The other parameters are as in Figure 6.

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. 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 7 depicts the process of 0.35 Gbit/s message encryption. On the top panel the digital message is shown. Figure 7b 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 6. Figure 7c 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 of tens of Mbit/s previously obtained in [19].

IV. CONCLUSION

In the framework of properly adapted Lang-Kobayashi equations, we have treated a single-mode semiconductor laser with an air gap under the influence of multiple feedbacks. The results presented in this paper show theoretically that under appropriate conditions such a laser is capable of generating a robust chaotic behaviour. Such behaviour has been confirmed in the experiment. It was found that an air gap makes the laser behaviour more chaotic compared with that of conventional feedback. In addition, it has been shown that two of these devices can be synchronized when operating in the chaotic regime in a master-slave configuration. With proposed scheme a short resynchronization time can be obtained. Finally, OOPSK encryption method can be successfully applied at a rate of hundreds of Mbit/s.

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