SYNCHRONIZATION AND OPTICAL COMMUNICATIONS BY THE CHAOS MODULATION TECHNIQUE USING QUANTUM DOT LASERS WITH T-TYPE OPTICAL FEEDBACK

N. Ciobanu[1,2], S. S. Rusu[2,3], and V. Z. Tronciu[3]

[1]*Department of Human Physiology and Biophysics, State University of Medicine and Pharmacy "NicolaeTestemitanu", Chisinau, Republic of Moldova*
[2]*Institute of Applied Physics, Academy of Sciences of Moldova, Chisinau, Republic of Moldova*
[3]*Department of Physics, Technical University of Moldova, Chisinau, Republic of Moldova*
E-mail:cnellu@gmail.com

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Abstract

We investigate the synchronization and optical communication processes using quantum dots lasers under the influence of external T-type optical feedback. The dynamical behavior of a single mode laser is studied in terms of the Bloch equation model. Appropriate conditions for chaotic behavior and synchronizations are fond. Under these conditions, the chaos modulation technique is applied for encoding and decoding a digital message in a chaos-based communication.

1. Introduction

In recent years, significant attention has been given to the study of nanoscale lasers and devices [1–3]. The main future of these devices is the possibility of obtaining high emission properties for small volume lasers and finally using these devices for integrated optical circuits. A substantial decrease in the cavity size of a nanoscale laser changes the stability properties, where an enhancement of spontaneous emission can be observed. These characteristics play an important role for increasing the communication speed and efficiency of information transmission, where the security is essential.

In particular, for increasing the degree of security of data transmission, a chaos-based communication technique was proposed [4–7]. The chaos modulation techniques require encoding the message in the amplitude of the chaotic output and keeping the amplitude of message small enough in order to avoid message recognition. A possibility of encoding the message in the chaotic output of single mode semiconductor lasers with external feedback was proposed in [8, 9]. The influence of external optical feedback and cavity parameters on the synchronization and message encoding is discussed. Other methods of message encoding within a chaotic carrier were elaborated in electronic circuits [10–12].

To describe the dynamics of a laser system with high spontaneous emission rates, one can use standard methods based on rate equation approach [13–15]. However, for lasers with larger numbers of quantum dots in the active region, the Bloch equation model seems to be more suitable and realistic [16]. Thus, in this paper, we present a study of the dynamics of a quantum dot laser under the influence of T-type feedback in terms of the Bloch equation model. A possible application of these devices for encoding and decoding digital messages in the chaos based communication technique is discussed. The influence of laser feedback parameters on the dynamics of the system is studied. The paper is organized as follows. A brief description of the setup and of the Bloch equation model is presented in Section 2. The synchronization of a master–slave laser system and encoding/decoding of a digital message using the chaotic modulation technique is discussed in Section 3. Finally, the conclusions are given in Section 4.

2. Model and equations

Figure 1 shows the setup considered for investigations of synchronization and optical communications by using the chaos modulation technique of quantum dots lasers. In our model, the feedback has a T-type structure. ϕ and ψ represent the accumulated optical phases of the laser fields reflected from mirrors R_1 and R_2, respectively. τ_1 and τ_2 are the delay time introduced by the first and second branches, respectively.

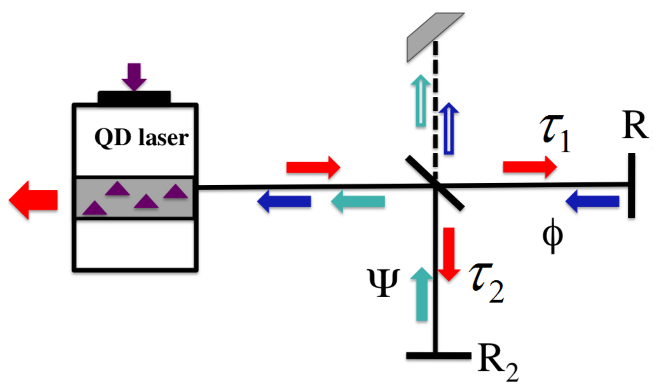

Fig. 1. Setup of a quantum dot laser under the influence of double T-type feedback.

The dynamics of the system is described by the Bloch equation model [16] where photon decay rate and polarization decay are taken into account. The system of equation containing equations for complex field amplitude E, polarization P, and inversion D for master “m” and slave “s” is given by

$$\frac{dE_{m,s}}{dt} = -\kappa E_{m,s} + 2Z^{QD}\Gamma g P_{m,s} + \frac{Z^{QD}\Gamma\beta}{\tau_{eff}E^{*}_{m,s}}\left(\frac{D_{m,s}+1}{2}\right)^2 + \Gamma_1 E_{m,s}(t-\tau_1)e^{i\phi}$$
$$+\Gamma_2 E_{m,s}(t-\tau_2)e^{i\Psi} + kE_s, \tag{1}$$

$$\frac{dP_{m,s}}{dt} = -\gamma P_{m,s} + gD_{m,s}E_{m,s}, \tag{2}$$

$$\frac{dD_{m,s}}{dt}=-4gE_{m,s}P_{m,s}+\frac{d_0-D_{m,s}}{T_1}+\frac{1}{\tau_{eff}}\left(\frac{D_{m,s}+1}{2}\right)^2. \tag{3}$$

The photon decay rate is designated as *K*, while the polarization decay parameter corresponds to γ. τ_{eff} is the effective rate of spontaneous emission and given by Purcell factor F_P and the spontaneous emission rate τ_{sp}, i.e., $\tau_{eff}=F_P/\tau_{sp}$. g and β represent the coupling and spontaneous emission factors. The β factor describes the percentage of spontaneously emitted photons, which are emitted inside a resonant cavity wave mode. The number of quantum dots in the active region of the laser is designated as Z^{QD}. Confinement factor Γ represents the fraction of quantum dots within the mode volume that contribute to laser emission. It is a measure of the fraction of the active region that amplifies a given mode; for a single-mode laser regime, Γ is a constant parameter. Finally, inversion lifetime T_1 and pump strength d_0 depend on the carrier density.

The terms that contain Γ_1 and Γ_2 parameters of equation (1) characterize the optical feedback that comes from T-type branches where Γ_1 and Γ_2 are the feedback strengths in respective branches. For the following numerical calculations the following dimensionless parameter values are used: $F_P=1$, $\Gamma=0.01$, $\beta=1$, $Z^{QD}=1000$, $d_0=0.95$, $K=300$, $\tau_{sp}=0.001$, $T_1=0.01$, $g=48.9$, and $\gamma=100$. Other parameter values, i.e., $\tau_1=0.2$ ns and $\tau_2=0.5$ ns, correspond to the round-trip times in the external branches. These parameters are considered identical for both master and slave lasers in the chaos modulation technique and used for the calculated results shown in all figures of the paper.

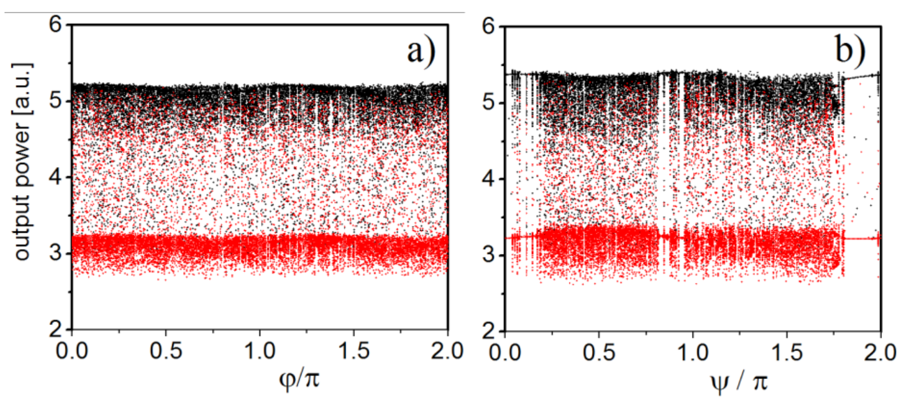

Fig. 2. Bifurcation diagrams for (a) $\Gamma_1=7$ ns^{-1}, $\Gamma_2=15$ ns^{-1}, $\psi=0.5\pi$ and (b) $\Gamma_1=10$ ns^{-1}, $\Gamma_2=20$ ns^{-1}, $\phi=0.5\pi$. Black (red) points show the maximum (minimum) of the output power.

First we consider the numerical bifurcation diagrams shown in Fig. 2, where the feedback phases of first ϕ and second external cavity branches ψ are the bifurcation parameters. One can observe in Fig. 2a that, at $\Gamma_1=7$ ns^{-1}, $\Gamma_2=15$ ns^{-1}, and $\psi=0.5\pi$ and in the case of ϕ being bifurcation parameter, the system exhibits a chaotic behavior for all values of phase ϕ. When the feedback parameters are increased to $\Gamma_1 = 10\ \mathrm{ns}^{-1}$, $\Gamma_2 = 20\ \mathrm{ns}^{-1}$, and $\phi = 0.5\pi$ as shown in Fig. 2b, a small region of continuous wave regime appears. On the other hand, in comparison with a single feedback (so-called conventional optical feedback) the presence of double sections results in more complex oscillations within wide regions of phases. In what follows, we are interested in the master–slave laser configuration and in the evolution of synchronization properties of this system. It is well known that the synchronization mechanism between two systems (master and slave) can be analyzed by measuring cross-correlation coefficient $C = \langle P_{\mathrm{master}} P_{\mathrm{slave}} \rangle \left(\left| \langle P_{\mathrm{master}} \rangle \langle P_{\mathrm{slave}} \rangle \right| \right)^{-1}$. The synchronization of two unidirectionally coupled master and slave lasers was studied numerically. The operation conditions are chosen such that the chaotic behavior persists for any values of external phases ϕ and ψ. Figure 3 shows the time evolution of emitted power for master (P_{master}) and slave (P_{slave}) lasers when the synchronization process is implemented.

One can observe a chaotic behavior where both time traces remain almost similar. The process of synchronization is the first indication that the chaos based communication can be applied for this system.

Below, we plot synchronization diagrams for different values of coupling coefficient. The emitted power of the master laser versus the slave for various values of the coupling parameter k is shown in Fig. 4. If the coupling parameter is equal to zero, as shown in Fig. 4a, the trajectories of the master and slave lasers depart from each other and the synchronization map represents a cloud of points showing the lack of correlation between outputs. Increasing the coupling parameter to $k = 20\ \mathrm{ns}^{-1}$, a good synchronization process can be observed (see Fig. 4d). Thus, we have shown that two quantum dot lasers in the chaotic regime can be synchronized.

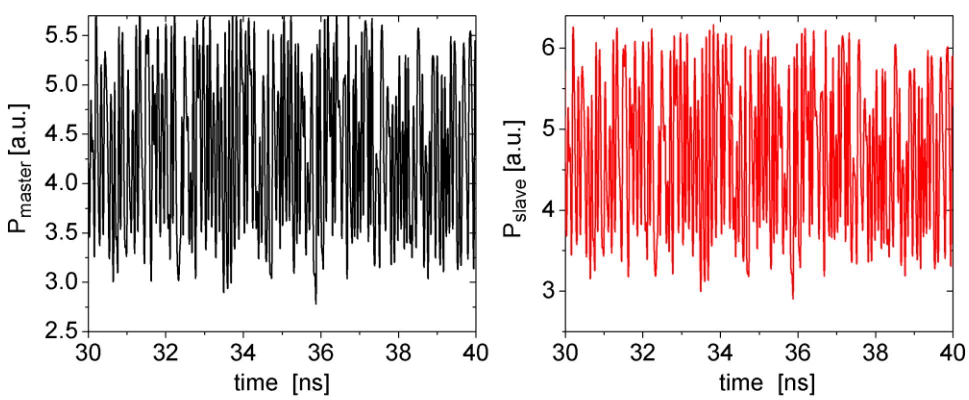

Fig. 3. Synchronization process of master (left) and slave (right) lasers for $k = 20\ \mathrm{ns}^{-1}$. Otherparameters: $\phi = 1.6$, $\psi = 0.8$, $\Gamma_1 = 20\ \mathrm{ns}^{-1}$, $\Gamma_2 = 30\ \mathrm{ns}^{-1}$.

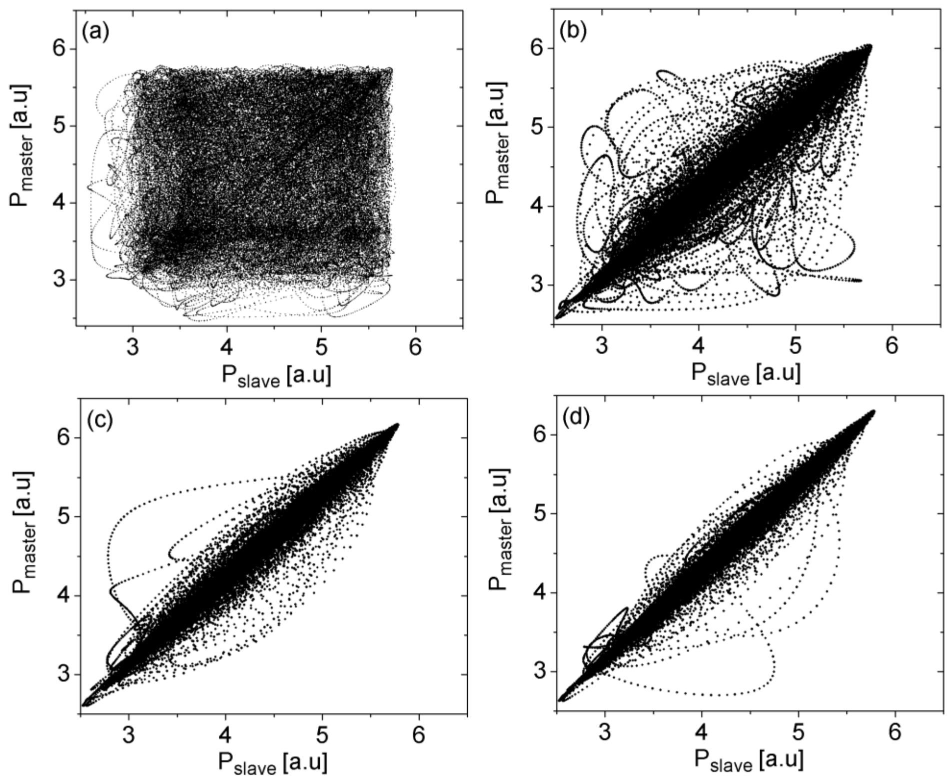

Fig. 4. Synchronization diagrams for different values of coupling parameter: (a) $k = 0\ \mathrm{ns}^{-1}$, (b) $k = 10\ \mathrm{ns}^{-1}$, (c) $k = 15\ \mathrm{ns}^{-1}$, and (d) $k = 20\ \mathrm{ns}^{-1}$.

Next, we discuss a model for transmission of an encoded message in the chaotic profile in the setup of two identical quantum dot lasers as shown in Fig. 5. The message is encoded in the chaotic amplitude of the master laser field and transmitted to the receiver, i.e., the slave laser. At the receiver, the message can be decoded depending on the degree of synchronization between the sender and the receiver.

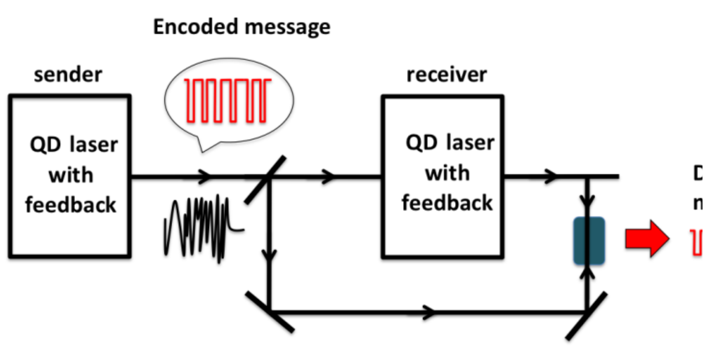

Fig. 5. Setup for chaos synchronization and message encoding and decoding using master–slave quantum dot lasers with feedback.

The chaotic output of a sender (master laser) can be used as a carrier in which a digital message is encoded. Normally, the amplitude of the encode message is much smaller than the wave front of the chaotic carrier; therefore, it is very complicated to extract the message from the chaotic carrier. The decoding operation is based on the fact that coupled chaotic master–slave lasers can be synchronized if appropriate conditions are given. To decode the message, the transmitted signal should be coupled to the receiver in another chaotic system, i.e., a slave laser that is identical to the sender.

The scenario and appropriate conditions for message encoding by the chaos modulation technique using compact lasers under the influence double-feedback configuration are represented in Fig. 6. The digital message before encoding is represented in the top panel (Fig. 6a). Panel (b) shows the output power of the master laser and (c) is the message encapsulated in the chaotic profile of the master laser that is transmitted to the receiver (slave laser). Finally, the recovered message after filtering is plotted in the bottom panel. The dotted curve corresponds to the encoded message, while the solid line corresponds to the recovered message. Thus, the received message corresponds to the encoded one.

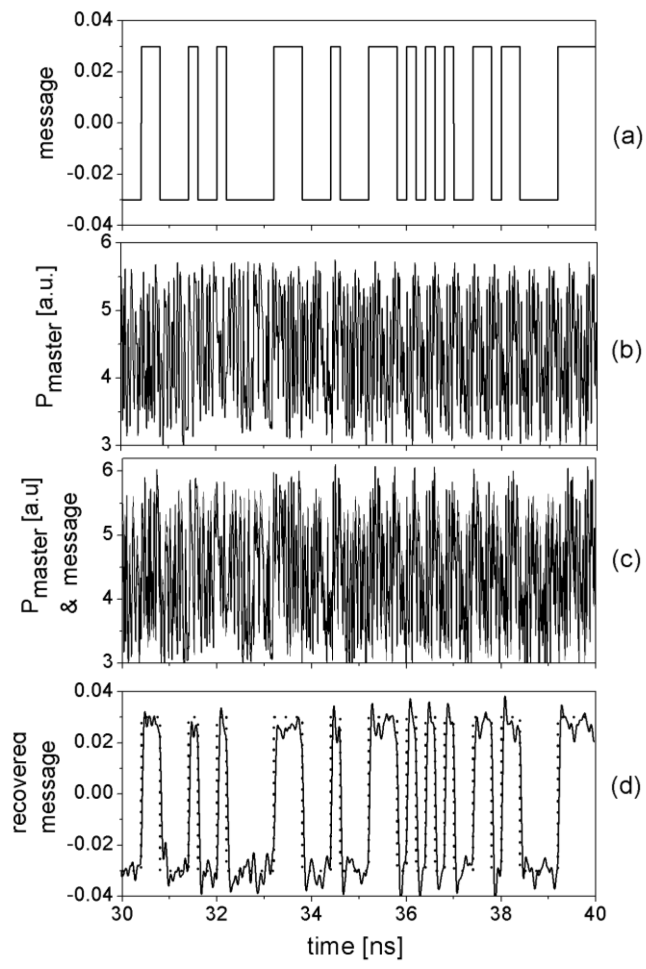

Fig. 6. Encoding and decoding of a digital message using the chaotic modulation technique for a master–slave laser system: (a) encoded message profile; (b) output power of the laser without message; (c) transmitted message encapsulated in the laser message; and (d) decoded and recovered message after filtering (solid line) and input message (dotted line). All parameters are the same as in Fig. 3.

3. Conclusions

In this paper, we have studied the dynamics of a quantum dot laser system under the influence of double-feedback of cavities. This study has been conducted in terms of the Bloch equation model. The synchronization of lasers and the bifurcation diagram are appropriate for different parameters of the external feedback. We have found the condition for which master–slave lasers exhibit chaotic behaviors appropriate to chaos based communications. A technique of transmission of anencoded message in this chaotic regime has been discussed. We believe that our work provides a good basis for future studies of various techniques for chaos based communications using compact quantum dot lasers with feedback from external cavities.

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