SYNCHRONIZATION OF CHAOTIC QUANTUM DOT LASERS WITH EXTERNAL FEEDBACK UNDER PARAMETER MISMATCH

T. Oloinic[1], S. S. Rusu[1,2], and V. Z. Tonciu[1]

[1]*Department of Physics, Technical University of Moldova, Stefan cel Mare Av. 168, Chisinau, MD-2004 Republic of Moldova*
[2]*Institute of Applied Physics, Academy of Sciences of Moldova, Academiei str. 5, Chisinau, MD-2028 Republic of Moldova*
tatiana.oloinic@fiz.utm.md

(Received July 30, 2018)

Abstract

This paper reports the numerical results on the synchronization features of a chaotic quantum dot semiconductor laser. The dynamic behavior is studied in terms of the Bloch equations model. Optimum conditions for chaotic operation are found. The synchronization of two unidirectional-coupled (master–slave) systems and the effect of parameter mismatch on the synchronization quality are studied.

1. Introduction

In the last decade, the synchronization of chaotic oscillators [1] has been the subject of different studies due to fundamental interest and applications in chaos-based communications systems [2, 3]. It is well known that semiconductor lasers subject to the influence of optical feedbacks are characterized by different dynamical behaviors, such as periodic and quasi-periodic pulsations, low frequency fluctuations, and coherent collapse. Typically, to achieve a chaotic behavior of conventional lasers with feedback from a distant mirror, a delay roundtrip time of at least a few nanoseconds is required. In this case, the mirror should be placed at a distance of a few tens of centimeters from the back facet of the laser. On the other hand, lasers with multisection external cavities can be suitable candidates for integrated chaotic emitters. Lasers subject to feedback from cavities with air gaps have been considered in the literature [4, 5]. In particular, feedback from a two-phase section was used to control the chaotic dynamics of semiconductor lasers with optical feedback. The dynamics of the system of a quantum dot laser with feedback proposed in this paper can be described by the Bloch equation model [6]. Thus, in this paper, we analyze the synchronization properties of two quantum dot lasers with multisection feedback coupled unidirectionally. The effect of parameter mismatch on the synchronization quality is studied.

The paper is structured as follows. We start in Section 2 by describing the laser setup and we introduce the model to describe the system dynamics. Section 3 presents a study of the dynamics of a laser under the action of multicavity feedback. Suitable conditions for the chaotic evolution of the output power system due to the influence of feedback are determined. The synchronization properties of two devices are presented. Finally, conclusions are given in Section 4.

2. Laser Model and Equations

Figure 1 shows the structure of a semiconductor laser with active medium quantum dots under the influence of feedback from equally distributed external cavities. We consider a single-mode DFB laser coupled to longitudinal multicavities. The first mirror is located at distance l from the laser facet, and the distance between mirrors is taken also l. The feedback part is composed by air-gap and phase sections. The phase sections are controlled by a small injected current. We assume that the injected current into the phase sections is small enough to change only the refractive index, i.e., the phase, so that the optical length of the resonator remains constant or is changed in the sub-wavelength range.

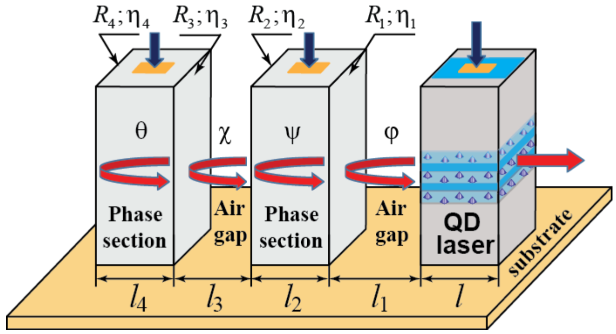

Fig. 1. Schematic view of a laser with a quantum dot active medium under the influence of multicavity external optical feedback. Phases ψ and θ are controlled by an injected current. R_1 and R_3 are the reflectivity of the air-material facet, respectively. R_2 and R_4 are the outer facet of the material cavity reflectivity, respectively.

The dynamical behavior of the system is described by the Bloch equations [6, 7]:

$$\frac{dE}{d\tau} = -kE + 2Z^{QD}\Gamma gP + \frac{Z^{QD}\Gamma\beta}{\tau_{eff}E}\left(\frac{D+1}{2}\right)^2 + \eta_1 e^{i\varphi}E(\tau-\tau_1) + \eta_2 e^{i\psi}E(\tau-\tau_2) +$$
$$+\eta_3 e^{i\chi}E(\tau-\tau_3) + \eta_4 e^{i\theta}E(\tau-\tau_4) + \zeta E, \quad (1)$$

$$\frac{dP}{d\tau} = -\gamma P + gDE, \quad (2)$$

$$\frac{dD}{d\tau} = -4gEP + \frac{d_0 - D}{T_1} - \frac{1}{\tau_{eff}}\left(\frac{D+1}{2}\right)^2, \quad (3)$$

where E is the complex amplitude of the electric field, P is the polarization, and D is the inversion. These equations are used for master and slave lasers. k is the photon decay rate. $g = \sqrt{\frac{G\gamma c_n}{2Z^{QD}\Gamma}}$ and β represent the coupling and spontaneous emission factors [6], where G is the gain and c_n as the speed of light in the laser medium; Z^{QD} is the number of quantum dots in the active region of the laser; Γ represents the confinement factor that characterizes the fraction of the quantum dots within the mode volume, which contribute to the laser emission; T_1 and d_0 are the inversion lifetime and pump strength; η_i are the feedback strengths governed by reflectivity R_i, respectively; ζ is the coupling strengths; τ_i are the external cavity round trips. The dimensionless parameters are k = 300, Z^{QD} = 1000, Γ = 0.01, β = 1.0, d_0 = 0.95, γ = 100,

$T_1 = 0.01$, $g = 48.86$, $\tau_{eff} = 0.001$, $\eta_1 = \eta_2 = \eta_3 = \eta_4 = 25$, $\zeta = 20$. These parameter values are used for the calculated results that are shown in all figures of the paper.

3. Results and Discussion

It is well known that the synchronization of two lasers can be quantified by measuring the cross-correlation coefficient, and the synchronization quality depends on the similarity between the master and slave lasers. As noted above, we focus here on the effect of the mismatch between different laser and material parameters on the synchronization features of two chaotic lasers coupled unidirectionally. Figure 2 shows the dependence of the cross-correlation coefficient on the phase difference (phase master − phase slave) for feedback strengths $\eta_i = 25$ and coupling strengths $\zeta = 20$. The other phases of passive sections are fixed.

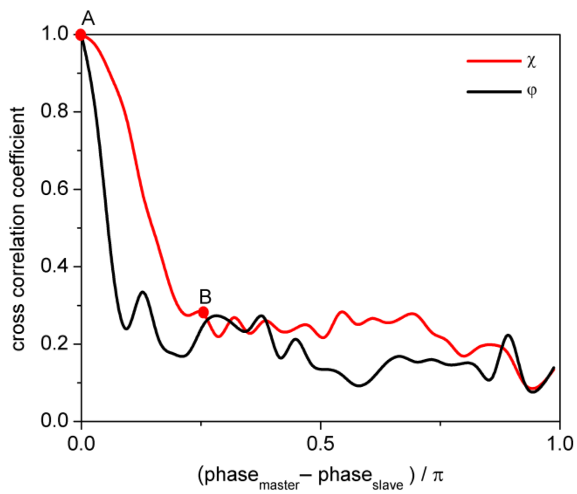

Fig. 2. Cross-correlation coefficient as a function of the feedback phase difference (phase master − phase slave) for coupling $\zeta = 20$. Parameters: $\varphi_s = 0$, $\psi_m = \psi_s = \pi/5$, $\chi_s = 0$, $\theta_m = \theta_s = \pi/4$.

The black line shows the degradation of the synchronization due to a mismatch of phase's φ of the master and slave lasers of the first air gap section. Phase φ_s of the slave laser is kept to zero, while phase φ_m of the master is varied from 0 to π. One can see the following conclusion. When the feedback phases coincide, the system shows perfect synchronization with a cross-correlation coefficient approaching unity (see point A in Fig. 2). An increase in the mismatch of the feedback phases induces a fast degradation of the synchronization, which is indicated by a reduction of the cross-correlation coefficient. This fast degradation is followed by the slowly one. The red line shows the effect of a mismatch in the second air-gap cavity feedback phase χ. We consider phase χ_s of the slave laser to be zero and vary phase χ_m of the master. As the mismatch is increased, the degradation is clearly less severe than for the case of mismatch in the feedback phase φ of the first air-gap. Thus, the phase of the shorter cavity is more sensitive to mismatch than that of long cavities.

Figure 3 shows the optical power time trace of the master (black) and slave (red) lasers and the synchronization diagrams for points A and B of Fig. 2, respectively. When the synchronization is perfect, the cross-correlation coefficient is close to unity $C = 0.995$ (see Fig. 3a). The synchronization map shows a clear synchronization process. Figure 3b shows the same dependences for point B, when the degradation of synchronization is observed and the cross-correlation coefficient is $C = 0.3$. The trajectories of the master and slave lasers depart from each other and the synchronization map is a cloud of points showing the lack of correlation between outputs.

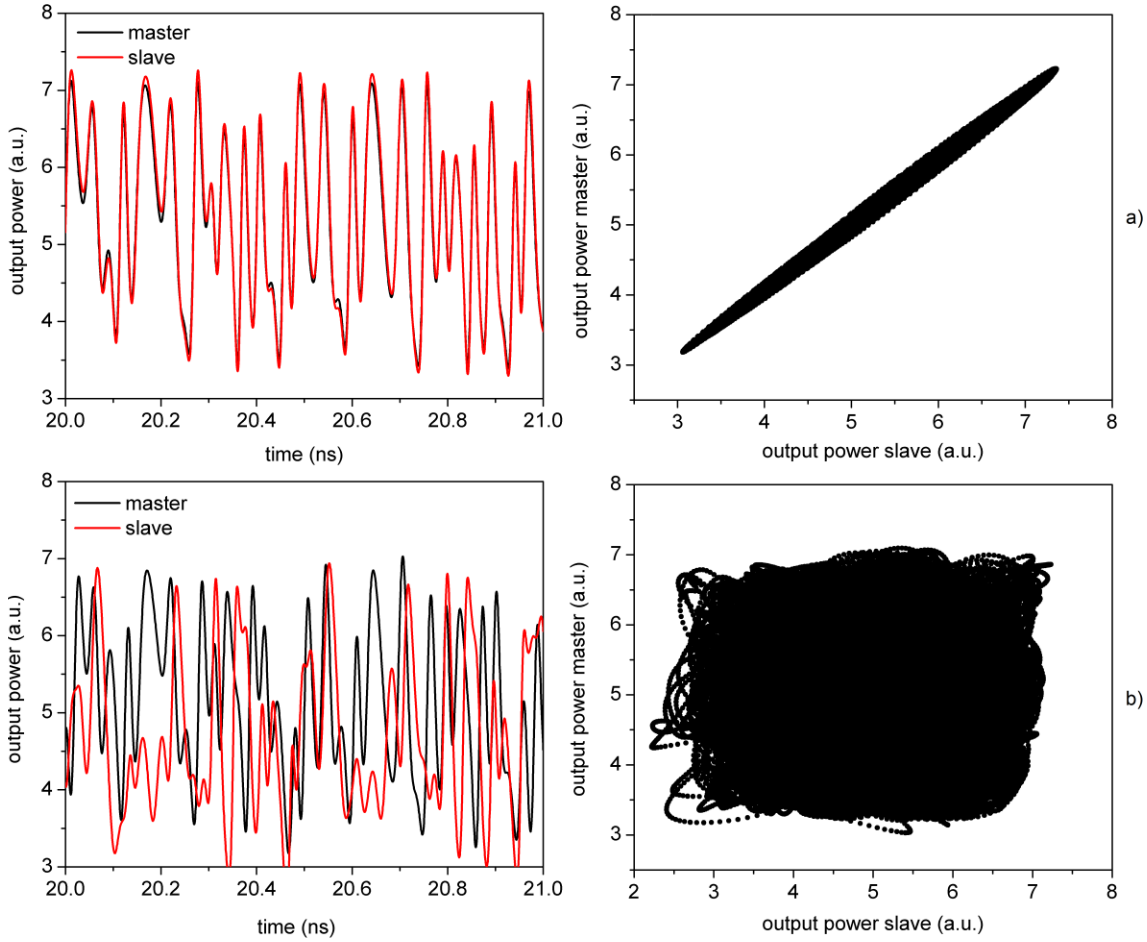

Fig. 3. Pulse traces of output power (left) and synchronization diagram (right) for points A (a) and B (b) of Fig 2. Parameters are the same as in Fig. 2.

Next, we study the effect of mismatch between other parameters on the synchronization performance of quantum dot lasers with feedback. Figure 4 shows the dependence of cross-correlation coefficient on mismatch between the difference of the gain (left) and the number of quantum dots (right) of the master and slave lasers. One can observe a higher degradation of synchronization in the case of gain mismatch compared with that of the number of quantum dots in active regions. This finding can be attributed to the fact that the difference in the number of quantum dots of the master and slave lasers leads only to a difference in the output power, but not in the high degradation of synchronization. However, note that the gain mutually depends on the number of quantum dots.

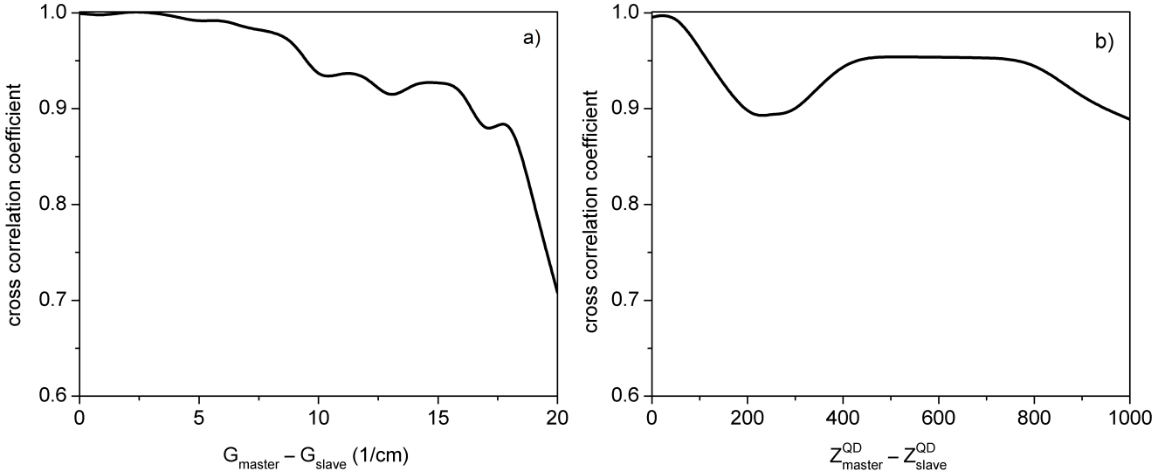

Fig. 4. Cross-correlation coefficient as a function of the difference of (a) the gain and (b) the number of quantum dots of the master and slave lasers. Parameters: $\varphi_s = \varphi_m = 0$, $\psi_m = \psi_s = \pi/5$, $\chi_m = \chi_s = 0$, $\theta_m = \theta_s = = \pi/4$. The fixed value parameters for the slave laser are G(slave)=60, $Z^{QD}(\text{slave}) = 1000$.

4. Conclusions

We have studied the synchronization properties of chaotic quantum dots laser under the influence of multisections optical feedback. The feedback implies a complex behavior keeping the device compact. A novel setup for the implementation of multiple feedbacks has been proposed. We have shown that two of these devices with equal parameters can be synchronized when they operate in the chaotic regime in a master–slave configuration, and the synchronization with higher cross correlation is achieved. However, synchronization is degraded when there is a mismatch in the material and device parameters of the master and slave lasers. It has been found that a mismatch in the first air gap feedback phase has stronger effects in the master–slave cross-correlation than a mismatch in the second air gap phase. In addition, it has been shown that the difference in the gain of the master and slave lasers leads to a degradation of synchronization. The number of quantum dots does not affect strongly the synchronization features of quantum dot lasers.

Finally, we believe that our work provides a good basis for future studies and, in particular, provides pointers for more detailed studies of synchronization of compact quantum dot lasers with feedback and their applications for chaos communication.

Acknowledgments. The authors acknowledge the financial support of the Technical University of Moldova (projects 14.02.116F/34S and 16. 80012.02.27F).

References

[1]A. Pikovsky, M. Rosenblum, and K. Kurths, Synchronization: A Universal Concept in Nonlinear Sciences, Cambridge University Press, Cambridge, 2003.
[2]A. Argyris, D. Syvridis, L. Larger, V. Annovazzi-Lodi, P. Colet, I. Fischer, J. García-Ojalvo, C.R. Mirasso, L. Pesquera, and A.L. Shore, Nature 438, 343 (2005).

[3]C.R. Mirasso, P. Colet, and P. Garcia-Fernandez, IEEE Photon. Technol. Lett. 8, 299 (1996).
[4]V.Z. Tronciu, C. Mirasso, P. Colet, M. Hamacher, M. Benedetti, V. Vercesi, and V. Annovazzi-Lodi, IEEE J. Quantum Electron. 46, 1840 (2010).
[5]V.Z. Tronciu, C. Mirasso, and P. Colet, J. Phys. B: At. Mol. Opt. Phys. 41, 155401 (2008).
[6]R. Aust, T. Kaul, C.-Z. Ning, B. Lingnau, and K. Ludge, Opt. Quantum Electron. 48, 109 (2016).
[7]B. Lingnau, Nonlinear and Nonequilibrium Dynamics of Quantum-Dot Optoelectronic Devices, Doctoral Dissertation, Berlin, 230 p., (2015).